

Quantum Detectors for particle physics

(focus on applying quantum sensors to
both “HEP” *and* low energy particle physics)

M. Doser, CERN/MIT/Oxford

- ① Clarification of terms
- ② Some words on the landscape
- ③ Quantum sensors for low energy particle physics
- ④ Quantum sensors for high energy particle physics
- ⑤ “DRD5”

quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

} highly sensitive and highly specific sensors for minute perturbations of the environment in which they operate

bottom line: quantum sensors measure result of a single individual interaction

*Then, a “quantum sensor” is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate **and** read out its quantum states.*

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

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*Then, a “quantum sensor” is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate **and / or** read out its quantum states.*

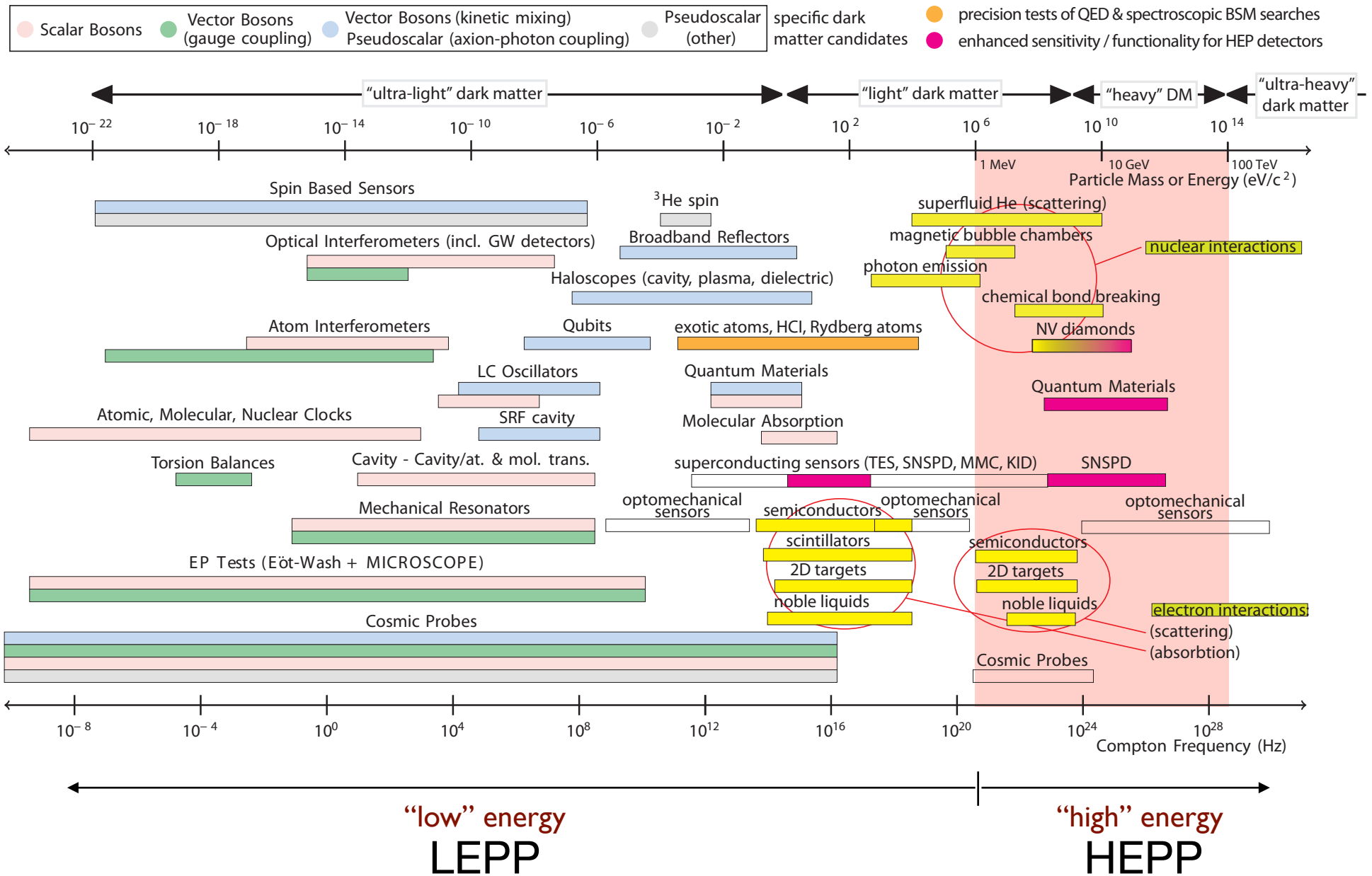
and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

→ focus on activities in both in **low energy** and **high energy** particle physics

(I will **not** however be talking about **entanglement** and its potential applications)

“Quantum” is everywhere

Landscape: quantum sensing applied to an extremely wide range of DM searches



2 ECFA Detector R&D Roadmap:

Quantum and Emerging Technologies

→ <https://indico.cern.ch/event/999818/>

→ <https://indico.cern.ch/event/957057/page/23281-the-roadmap-document>

domains of physics

search for NP / BSM

Axions, ALP's, DM & non-DM UL-particle searches

tests of QM

wavefunction collapse, decoherence

EDM searches & tests of fundamental symmetries

Development of new detectors

roadmap quantum technologies

1 superconducting devices (TES, SNSPD, ...) / cryo-electronics

2 spin-based, NV-diamonds

3 optical clocks

4 ionic / atomic / molecular

5 optomechanical sensors

6 metamaterials, 0/1/2-D materials

Qbit-relevant technologies

2

ECFA Detector R&D Roadmap:
Implementation

Proposal for DRD5: R&D on quantum sensors
 —————> Proposal themes —————> Proposal WP's

Roadmap topics

Proposal WP's

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 <i>Atomic, Nuclear and Molecular Systems in traps & beams</i>	X			X	(X)	
WP2 <i>Quantum Materials (0-, 1-, 2-D)</i>		(X)	(X)		X	X
WP3 <i>Quantum superconducting devices</i>		X				(X)
WP4 <i>Scaled-up massive ensembles (spin-sensitive devices, hybrid devices, mechanical sensors)</i>		X	(X)	X	(X)	X
WP5 <i>Quantum Techniques for Sensing</i>	X	X	X	X	X	
WP6 <i>Capacity expansion</i>	X	X	X	X	X	X

Ensure that all sensor families that were identified in the roadmap as relevant to future advances in particle physics are included: WP —> sub-WP —> sub-sub-WP

2 Many initiatives related to HEP world-wide;

Three initiatives at CERN:

- CERN Quantum Technology Initiative
- Physics Beyond Colliders
- R&D on quantum sensors for particle physics (DRD5)

CERN quantum initiative (v1)

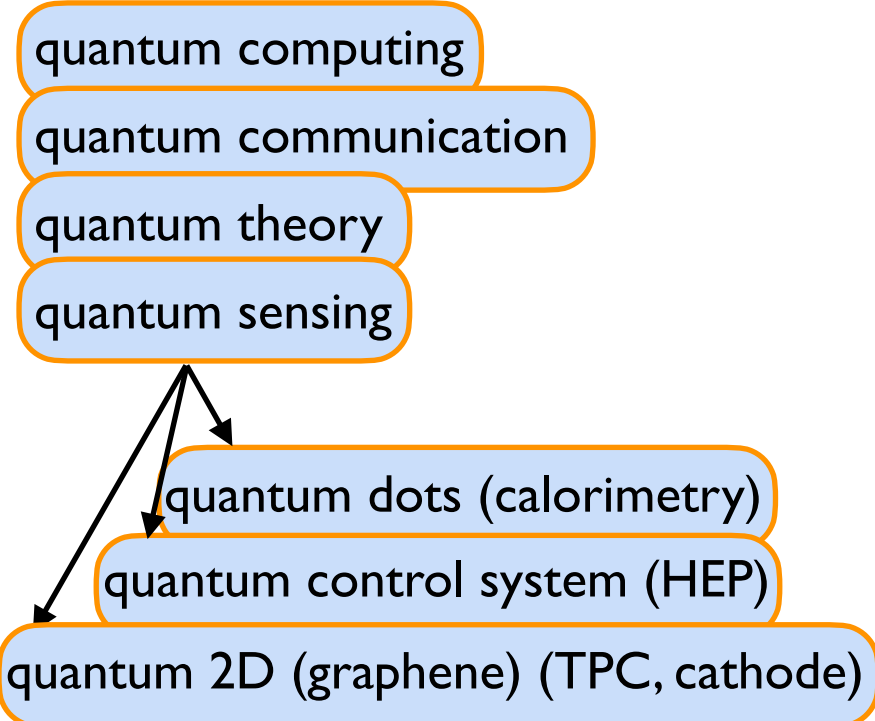
pilot



CERN quantum initiative (v2)

focus on technology

DRD5 WP's 1 3 6



<p>Objective 2.1a: Exotic atoms as qubits and Dark Matter sensors (Rydberg states characterisation, spectroscopy; atom interferometry; entangled Rydberg states as quantum demonstrators for qubits)</p> <p>Objective 2.2a: RF cavities and coating for axion searches; designing, building and operating a tuneable RF cavity for axion and GW searches</p> <p>Objective 2.2b.1: Development of a multi-qubit demonstrator platform (cryogenic infrastructure and RF cavity technology; design intermediate control software layer)</p> <p>Objective 2.3a: Quantum Sensors and Quantum Data Acquisition (TES as quantum sensors for millicharged DM searches in beam dumps, test bed for Quantum DAQ)</p> <p>Core goals</p>	<p>Objective 2.1b: Evaluation of the interplay between interferometric inertial sensors and cosmology to improve understanding of properties of Dark Matter and sources of GWs</p> <p>Objective 2.2b.2: Develop device-aware algorithms for qubits with SRF cavities</p> <p>Objective 2.3b: Cryogenic veto system, tuneable low-energy deposit calibration set-up; Monte Carlo simulation for tracks of backgrounds and signals, pushing the modeling towards low-energy deposits</p> <p>Extended objectives</p>	<p>Objective 2.1c: Benchmark and comparison of Rydberg states as qubits in prototype systems</p> <p>Objective 2.2b.3: Investigate scaling behavior of multiple qubits</p> <p>Objective 2.3c: Read-out-free detection & DAQ via entanglement between TES voxels and another system; machine-learning-based anomaly detection of millicharged DM particles in TES</p> <p>Long term objectives</p>
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3 WP1

particles, atoms, ions, nuclei:

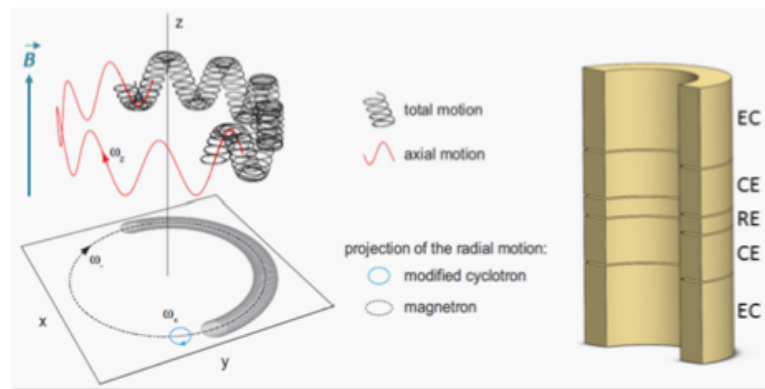
tests of QED, T-violation, P, Lorentz-violation, DM searches

eEDM's in molecules

nuclear clock (^{229}Th)

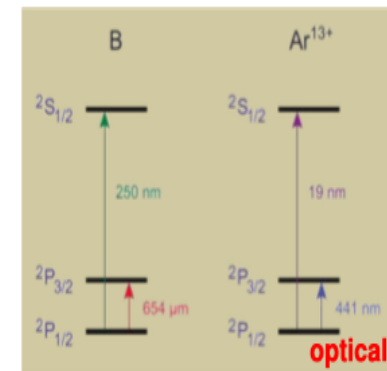
molecular / ion clocks

HCI's in Penning traps



Scaling with a nuclear charge Z

- Binding energy $\sim Z^2$
- Hyperfine splitting $\sim Z^3$
- QED effects $\sim Z^4$
- Stark shifts $\sim Z^{-4}$



K. Blaum et al., Quantum Sci. Technol. 6 014002 (2021)
 J.C. Berengut et al., Phys. Rev.A 86, 02251 (2012)

Quantum Sensors for New-Physics Discoveries

<https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries>

ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

<https://indico.cern.ch/event/999818/>

Marianna Safronova (University of Delaware)

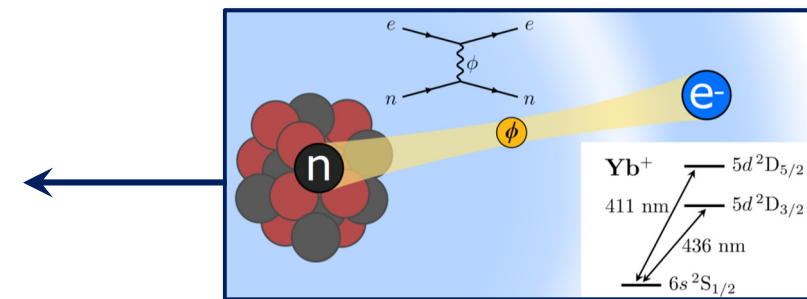
M.Doser, IIHE Brussels, Apr. 3

3 WP1

Quantum sensors for new particle physics experiments: Penning traps

HCI's: **much larger** sensitivity to variation of α and dark matter searches than current clocks

- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCI's to study non-linearity of the King plot



WP-1

Atomic & nuclear physics (exotic atoms, neutrino physics, clocks)

Ions in traps:

Antiprotons (AD), fully-stripped (radio)nuclei (AD), anions & cations (AD), cations (ISOLDE)

BASE collaboration, Coherent spectroscopy with a single antiproton spin
<https://www.nature.com/articles/s41586-025-09323-1>

Rydberg atoms:

Positronium (AD), antiprotonic atoms (AD)

Hydrogen-like Rydberg ions:

Single-electron highly charged ions in Rydberg states

optical

Hydrogen-like GS ions:

Single-electron GS optical HFS manipulation in HCI's

optical

"Towards metrology with highly charged isomeric ions from antiproton annihilation"
 Sara Alfaro et al 2025 *J. Phys. B: At. Mol. Opt. Phys.* **58** 215002
 (qubits in a highly shielded environment, but with long-range interactions)

Antiprotonic atoms → novel HCI systems

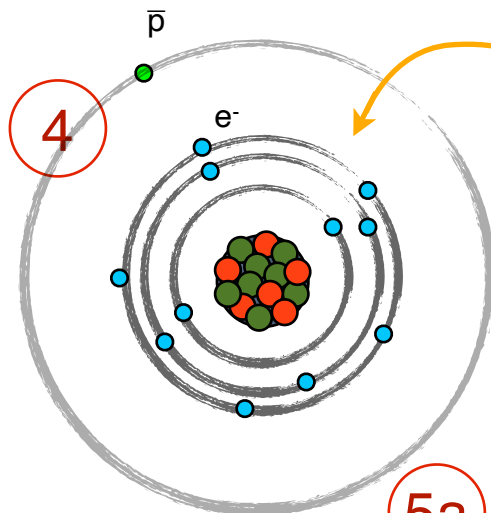
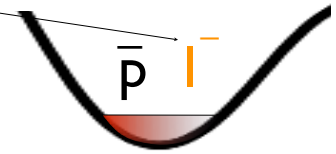
multi-step process that builds on existing techniques (including an **anion source** and **excitation lasers**)

1 formation and capture of HCl

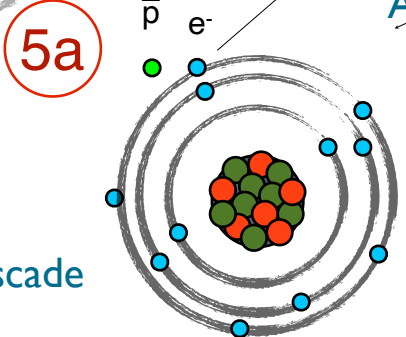
1 photo-detachment: $I^- \rightarrow I^0 + e^-$ (γ_1)

2_{opt} Rydberg excitation: $I^0 \rightarrow I^*$ ($\gamma_2 + \gamma_3$)

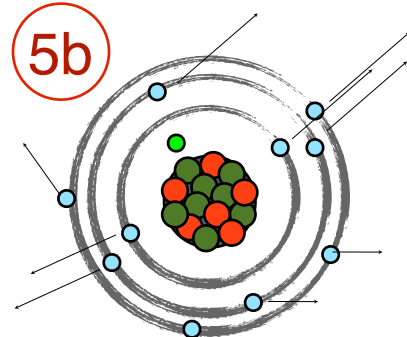
3 Charge exchange: $\bar{p} + I^* \rightarrow \bar{p}I^{+*} + e^-$ ($\bar{p} + Ps^* \rightarrow \bar{p}e^{+*} + e^-$)



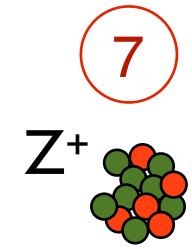
Rydberg cascade



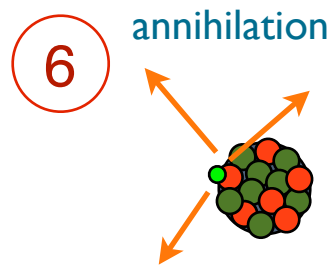
cascade



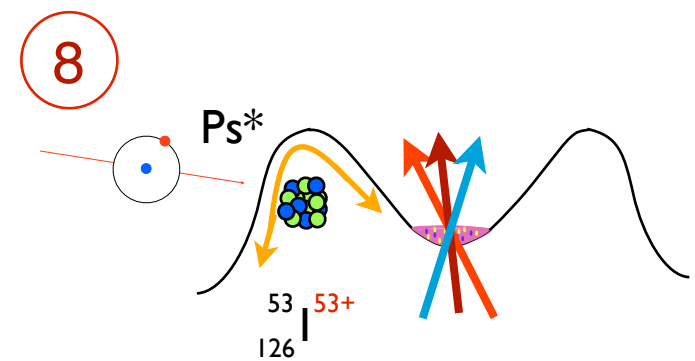
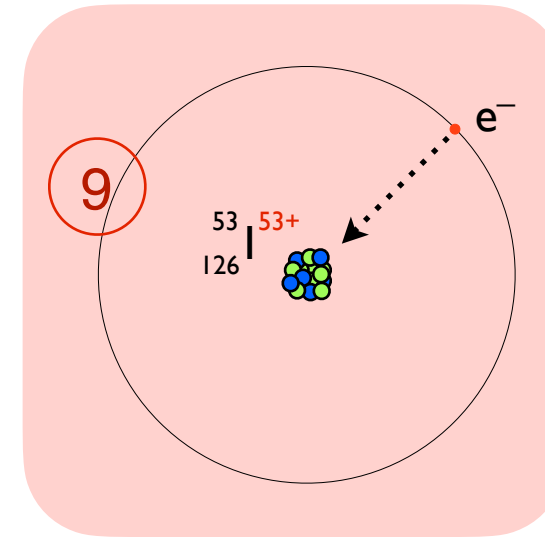
Auger ejection



trapping of HCl (fully stripped, Z~40+)

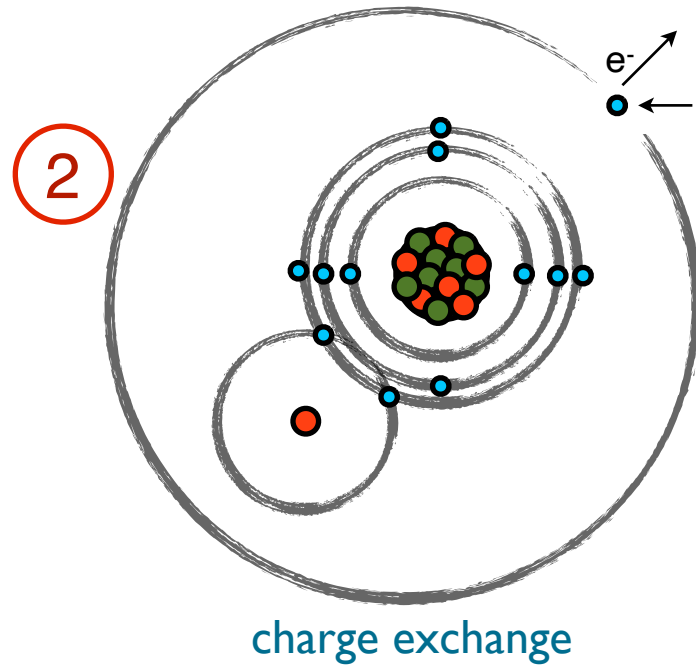
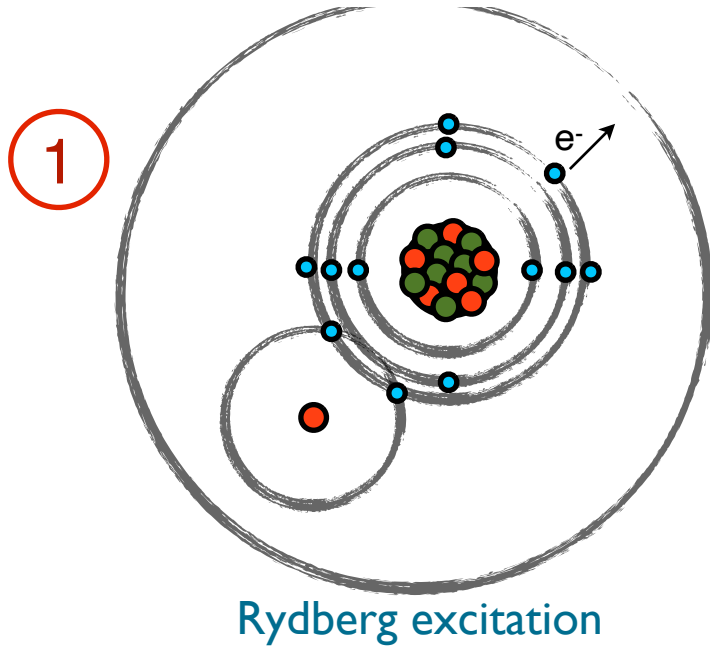


annihilation



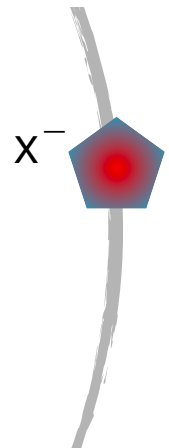
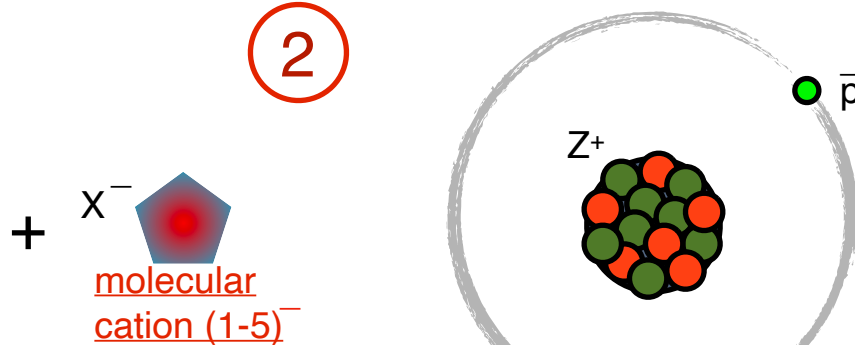
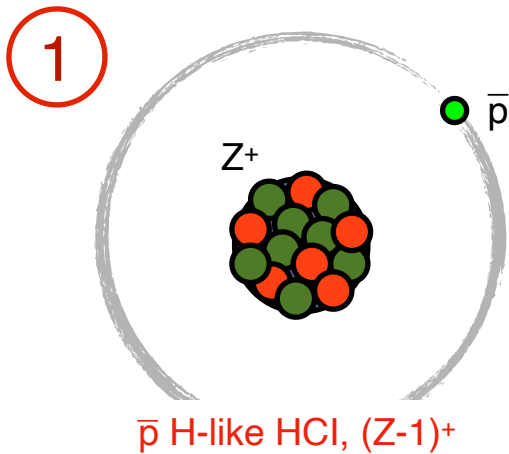
Antiprotonic Rydberg **atoms**: exotic couplings, similar approach as spectroscopy of muonic atoms, QED, CPT tests

Antiprotonic Rydberg **molecules**: \bar{p} EDM?



similar approach as eEDM in molecules

Antiprotonic Rydberg **molecular ions**: \bar{p} EDM



AION: atom interferometer (start small, ultimately → space)

L. Badurina et al., AION: An Atom Interferometer Observatory and Network, *JCAP 05 (2020) 011*, [arXiv:1911.11755].
arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

Topological Dark Matter (TDM)

~ scalar field that couples to fundamental constants, thus producing variations in the transition frequencies of atomic clocks at its passage

Ultralight Dark Matter

spatial variation of the fundamental constants associated with a change in the gravitational potential

Local Lorentz Invariance (LLI)

independence of any local test experiment from the velocity of the freely-falling apparatus: search for daily variations of the relative frequency difference between 2 clocks with different spatial orientation

Local Position Invariance (LPI)

independence of any local test experiment from when and where it is performed in the Universe; here, compare atomic clocks based on different transitions to constrain the time variation of fundamental constants and their couplings

Gravitational wave detector

clocks act as narrowband detectors of the Doppler shift on the laser frequency due to the relative velocity between the satellites induced by the incoming gravitational wave

R & D needed:

Optical lattice clocks at up to 1×10^{-18} relative accuracy

& expanded optical fibre network (operated between a number of European metrology institutes)

& develop cold atom technology for robust, long-term operation

Where does this fit in? Go after $10^{-20} \text{ eV} < m_a < 10^{-12} \text{ eV}$

1 atom interferometry at macroscopic scales:

arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

AION^{UK} MIGA^{France} MAGIS^{Fermilab} ZAIGA^{China}

CERN?

shafts (100~500 m ideal testing ground),
cryogenics, vacuum, complexity...

M. Abe, P. Adamson, M. Borcean, D. Bortoletto, K. Bridges, S. P. Carman et al., *Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)*, arXiv:2104.02835v1.

MAGIS collaboration, Graham PW, Hogan JM, Kasevich MA, Rajendran S, Romani RW. *Mid-band gravitational wave detection with precision atomic sensors*. arXiv:1711.02225

2 satellite missions:

ACES (Atomic Clock Ensemble in Space)

ESA mission for ISS 2025-2028 On 28 April 2025, ACES was successfully switched on on the ISS for the first time

pathfinder / technology dev. missions ~ 2030

I-SOC: key optical clock technology (laser cooling, trapping, optical resonators) for space; Sr optical lattice clock / Sr ion clock; microwave and optical link technology;

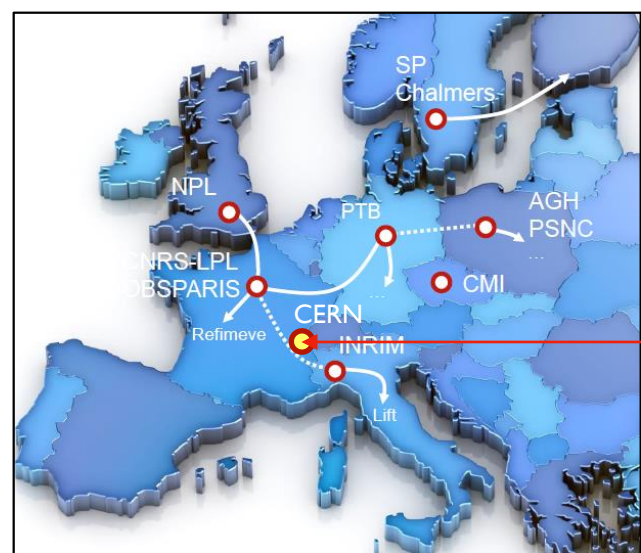
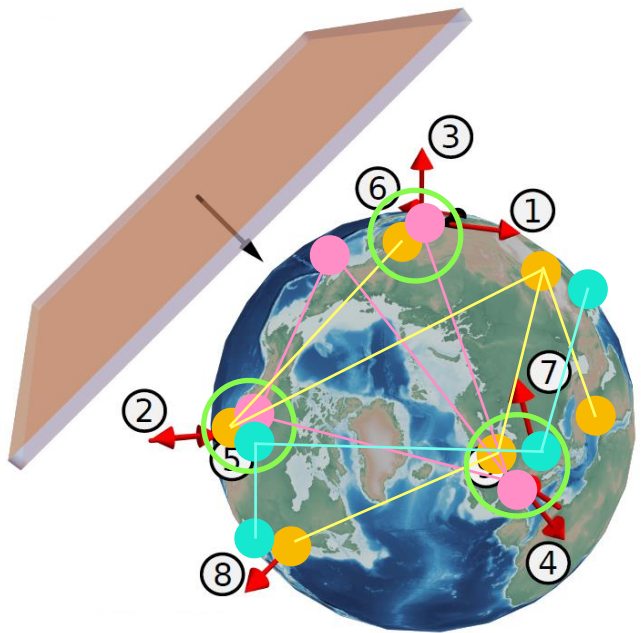
FOCOS (Fundamental physics with an Optical Clock Orbiting in Space): Yb optical lattice clock with 1×10^{-18} stability

AEDGE: ~2045

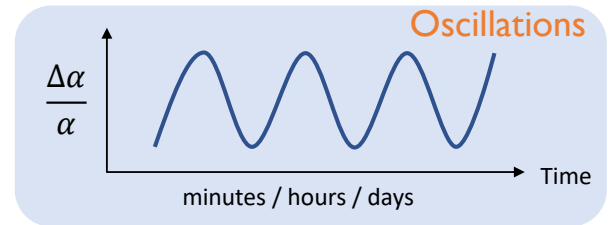
El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. et al. *AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space*. *EPJ Quantum Technol.* 7, 6 (2020). <https://doi.org/10.1140/epjqt/s40507-020-0080-0>

3 WP1 WP4 Quantum sensors for low energy particle physics

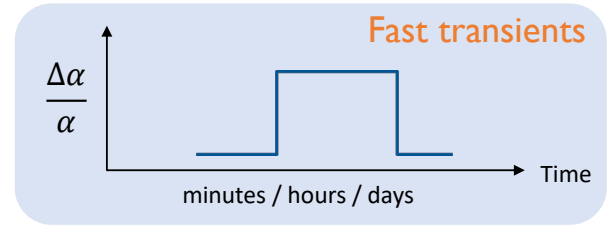
search for NP / BSM



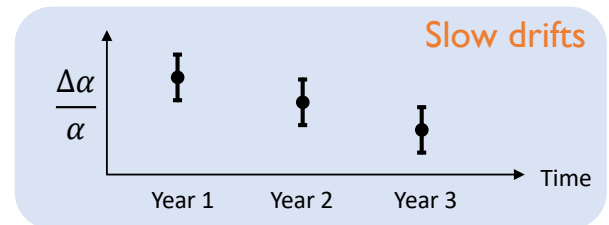
networks of sensors



Very light DM



DM- topological defects



New physics

magnetometers

Afach et al, arXiv:2102.13379v2

atomic clocks

nuclear, HCl, molecules

Wcislo et al, Sci. Adv. 4, 4869 (2018)

optical fiber networks

Roberts et al, New J. Phys. 22, 093010 (2020)

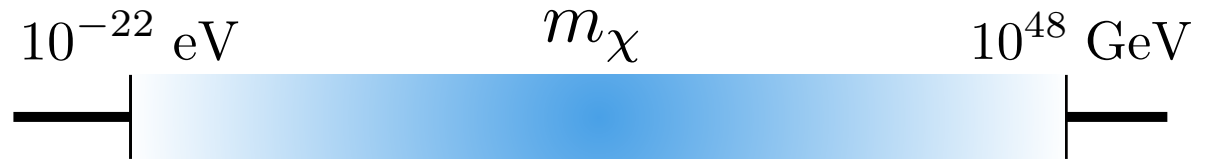
Investigate very light scalar and pseudo-scalar DM candidates over ~10 orders of magnitude in mass and different couplings

@ CERN: CPT, QED, QCD tests

Precision spectroscopy of antihydrogen, $\bar{p}\text{He}$, Ps @ $10^{-15} \Delta E/E$

Superconducting sensors: RF cavities

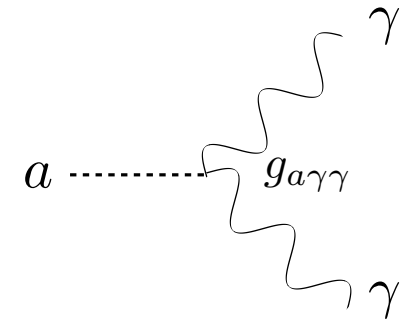
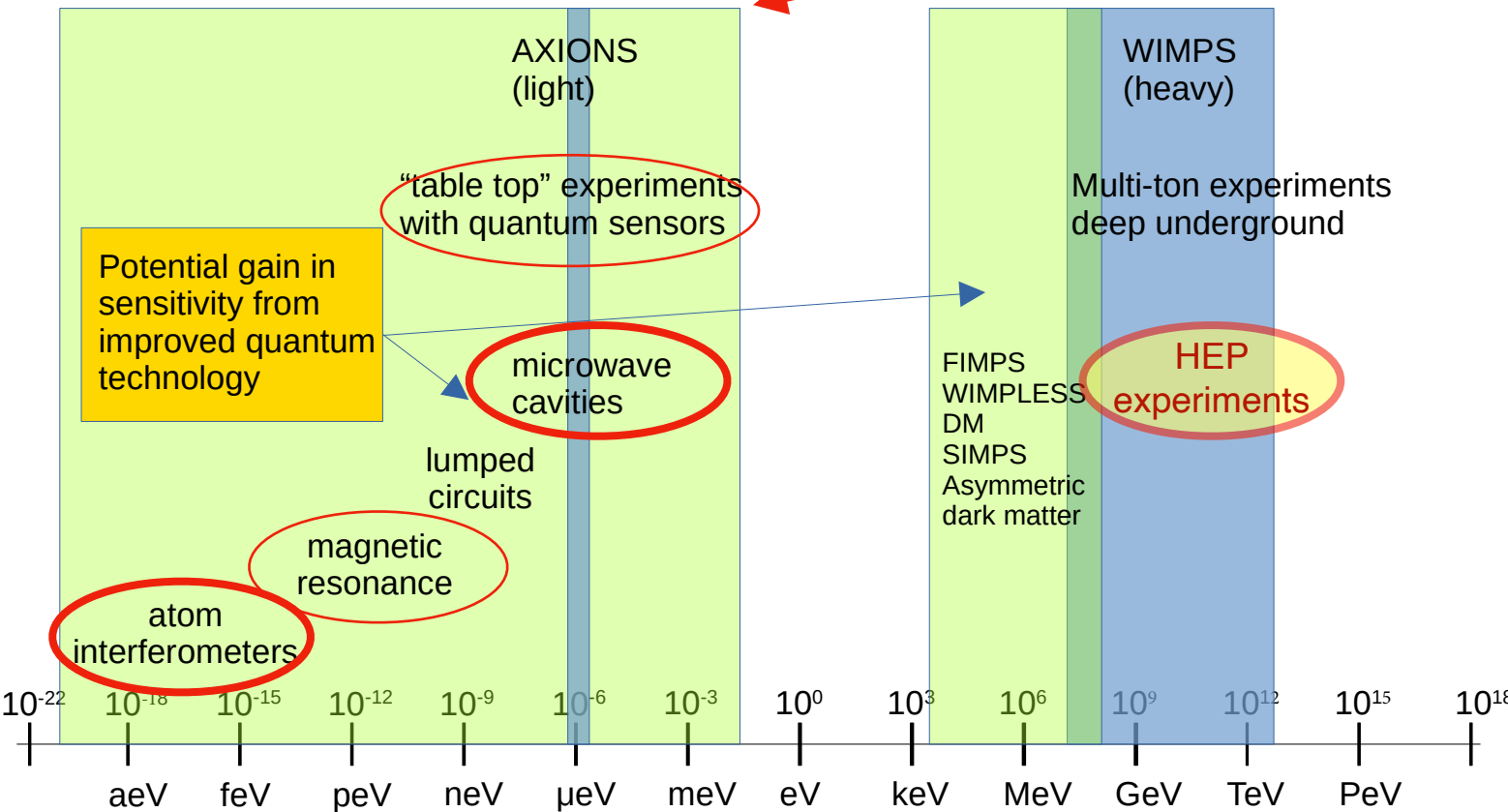
Axions, ALP's, DM & non-DM UL-particle searches



cavity size = axion size
axion mass = unknown

$$F \sim g_{a\gamma}^2 m_A^2 B^4 V^2 T_{sys}^{-2} G^4 Q,$$

system noise temperature
cryo-amplifiers JPA



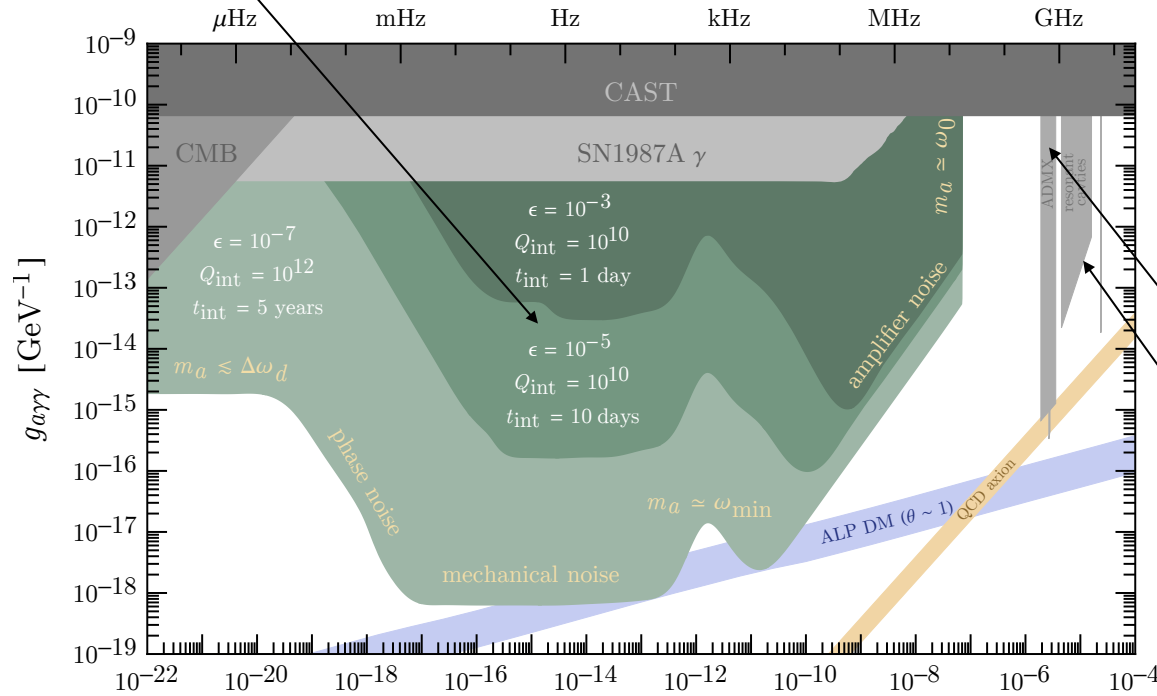
(but not only...)

Axion heterodyne detection

$Q_{\text{int}} \gtrsim 10^{10}$ achieved by DarkSRF collaboration
(sub-nm cavity wall displacements)

A. Grassellino, "SRF-based dark matter search: Experiment," 2019. <https://indico.fnal.gov/event/19433/session/2/contribution/2/material/slides/0.pdf>

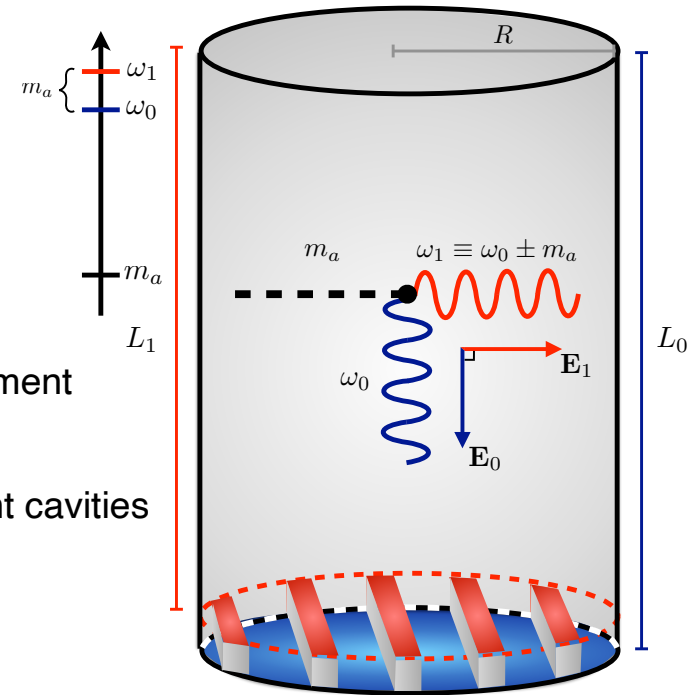
frequency = $m_a/2\pi$



problem: cavity resonance generally fixed

Resonant cavities possible down to μeV ;
below that, need huge volume

driving "pump mode" at $\omega_0 \sim \text{GHz}$ allows axion to resonantly drive power into "signal mode" at $\omega_1 \sim \omega_0 \pm m_a$



(a) Cartoon of cavity setup.

Conceptual Theory Level Proposal:

A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088
Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, Kevin Zhou, <https://arxiv.org/abs/1912.11048>

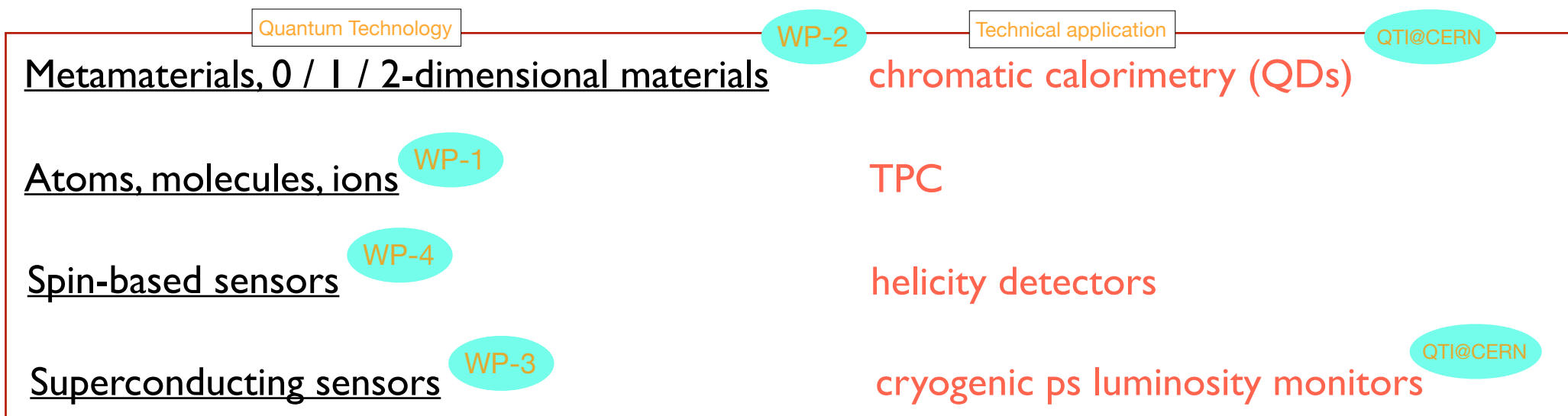
"The cavity is designed to have two nearly degenerate resonant modes at ω_0 and $\omega_1 = \omega_0 + m_a$. One possibility is to split the frequencies of the two polarizations of a hybrid HE_{11p} mode in a corrugated cylindrical cavity. These two polarizations effectively see distinct cavity lengths, L_0 and L_1 , allowing ω_0 and ω_1 to be tuned independently."

Needed! : major developments on integrated cryoelectronics (4K)

typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Cerenkov photons, ...)

handful of ideas that rely on quantum devices, or are inspired by them. not necessarily used as quantum detectors per se, but rather their properties to enhance / permit measurements that are more difficult to achieve otherwise

→ Frontiers of Physics, M. Doser et al., 2022
doi: 10.3389/fphy.2022.887738

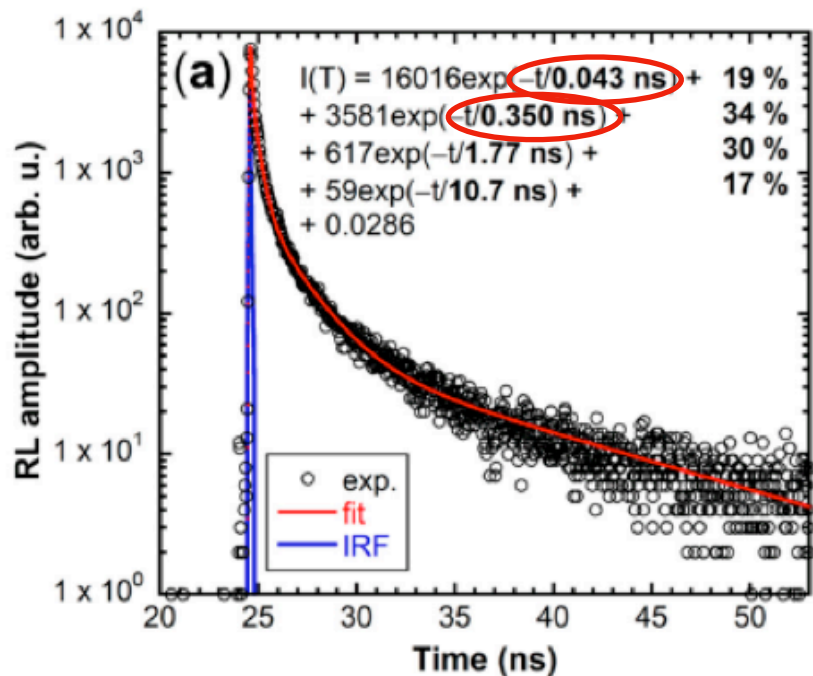


these are not fully developed concepts, but rather the kind of approaches one might contemplate working towards

Mostly speculative!

Quantum dots: timing

Etiennette Auffray-Hillemans / CERN



K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. *Nanomaterials* 2022, 12, 14. <https://doi.org/10.3390/nano12010014>

Scintillation decay time spectra from CsPbBr₃ nanocrystal deposited on glass

Quantum sensors for high energy particle physics

ZnO:Ga embedded in SiO₂ or polystyrene

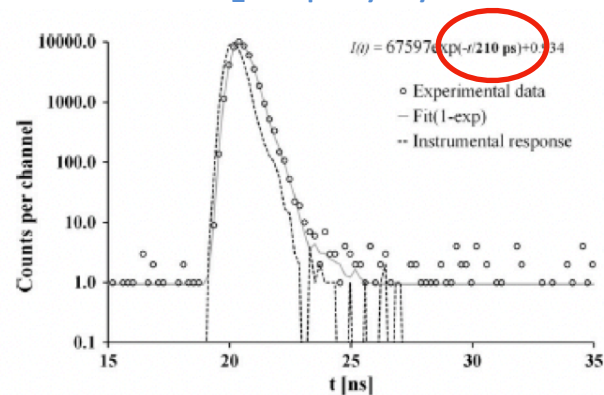
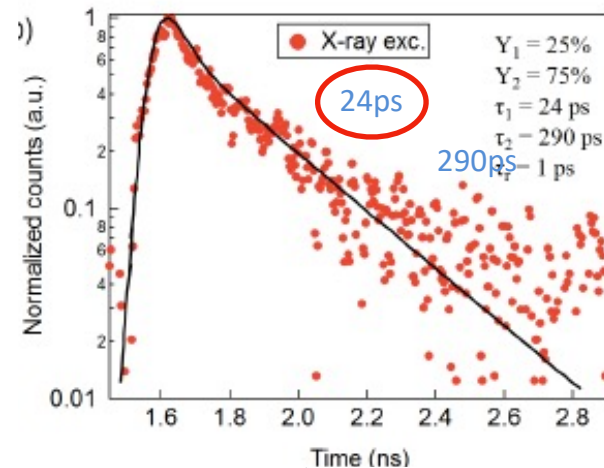


Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

Lenka Prochazkova et al., *Optical Materials* 47 (2015) 67–71

CdSe nanoplatelet,

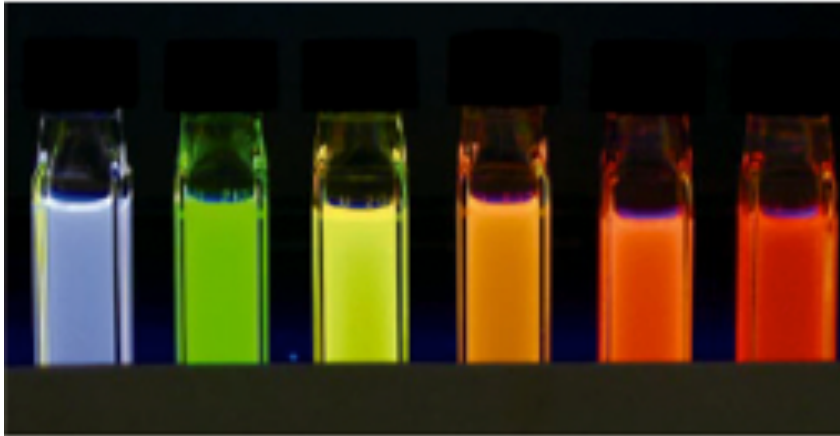


J. Grim et al., *Nature Nanotechnology*, 9,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

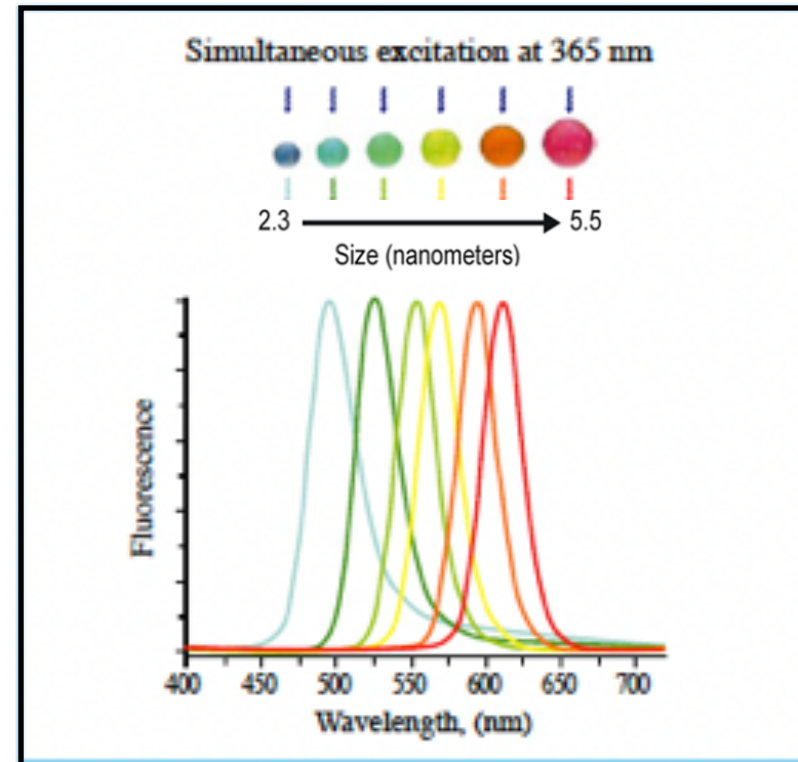
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

Quantum dots: chromatic tunability

Etiennette Auffray-Hillemans / CERN



Hideki Ooba, "Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements," AIST TODAY Vol.6 , No.6 (2006) p.26- 27

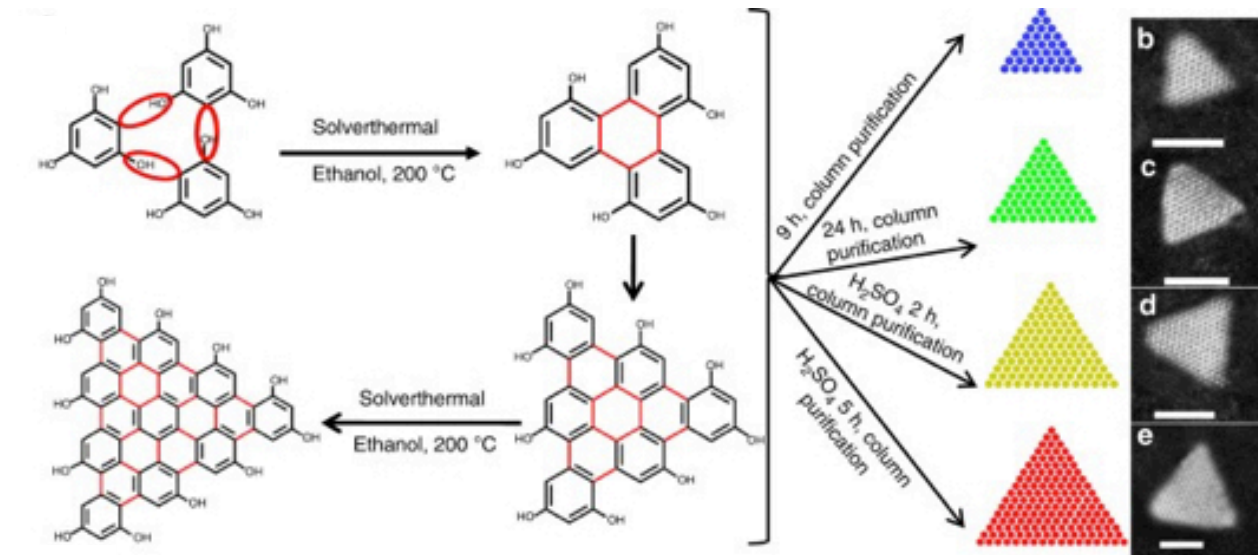


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

deposit on surface of high-Z material → thin layers of UV → VIS WLS

embed in high-Z material ? two-species (nanodots + microcrystals) embedded in polymer matrix?
 → quasi continuous VIS-light emitter (but what about re-absorbtion?)

Quantum dots: chromatic calorimetry



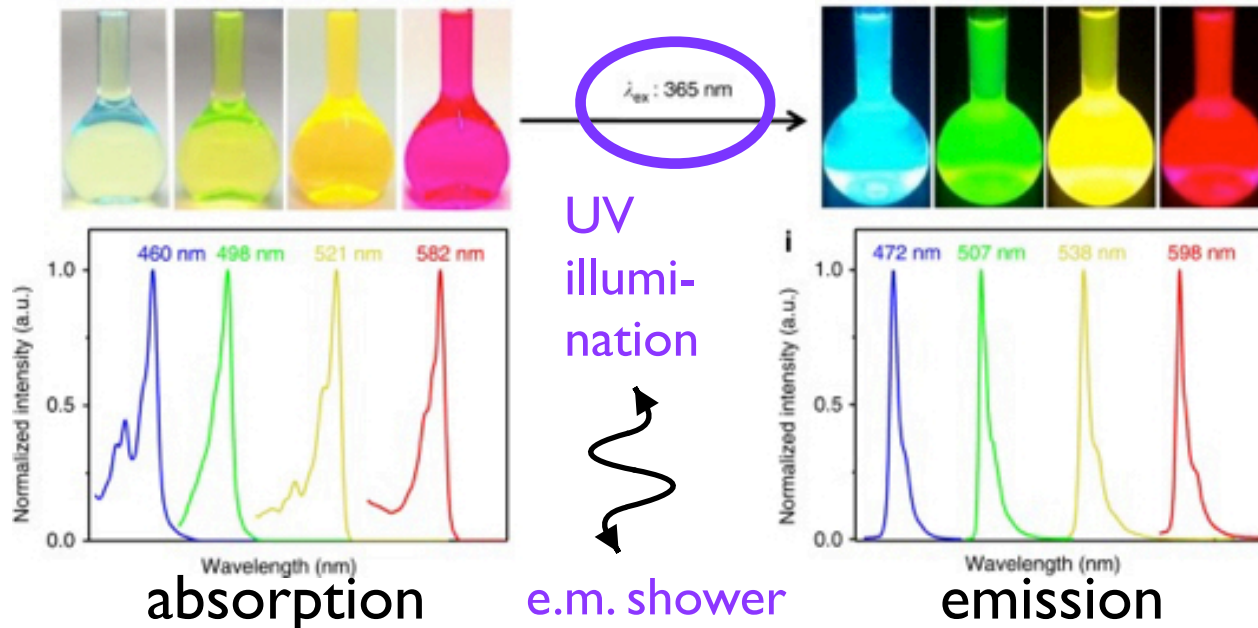
idea: seed different parts of a “crystal” with nanodots emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is uniquely assignable to a specific nanodot position

requires:

- narrowband emission (~20nm)
- only absorption at longer wavelengths
- short rise / decay times

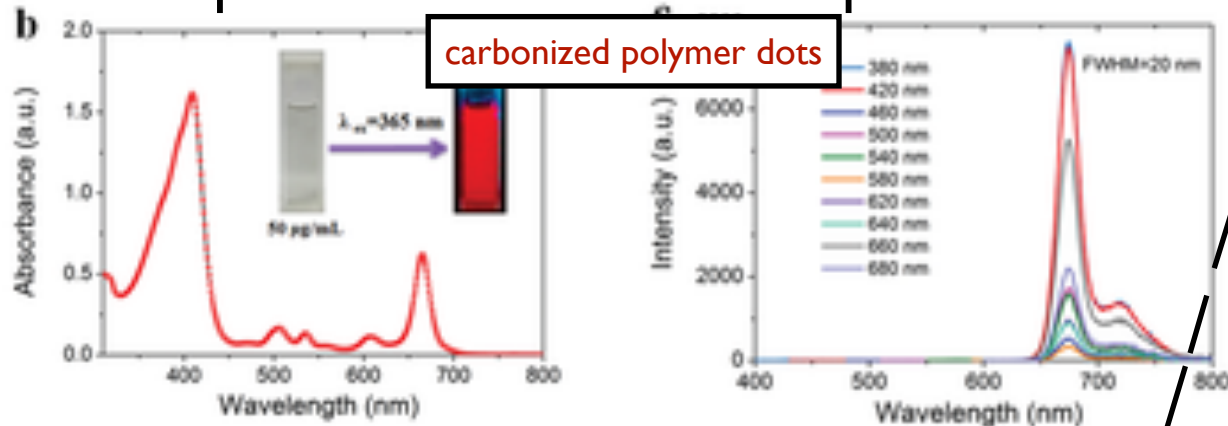
select appropriate nanodots

e.g. **triangular carbon nanodots**



absorption spectrum

emission spectrum



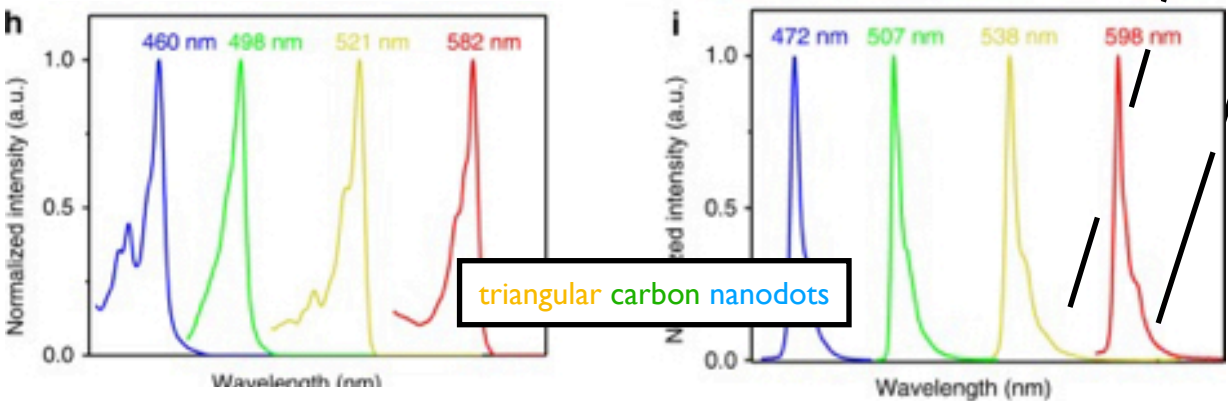
carbonized polymer dots

leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

next band:
absorb wavelengths < 590 nm
emit at > 590 nm

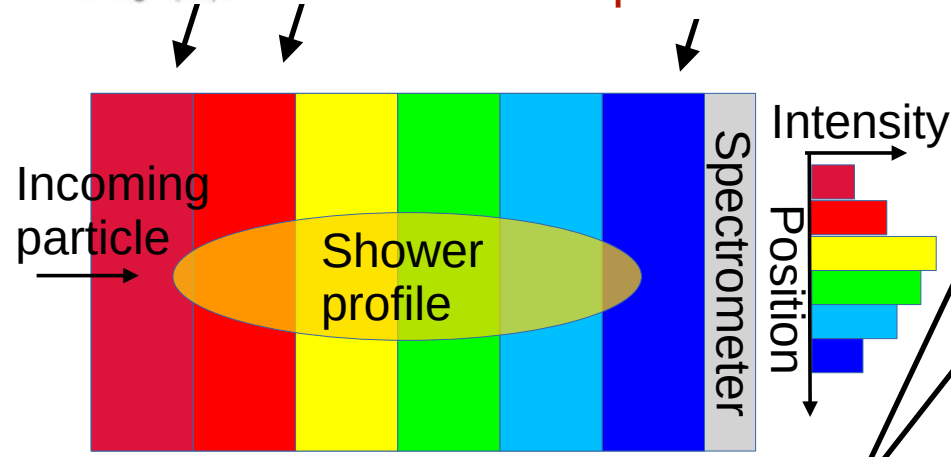
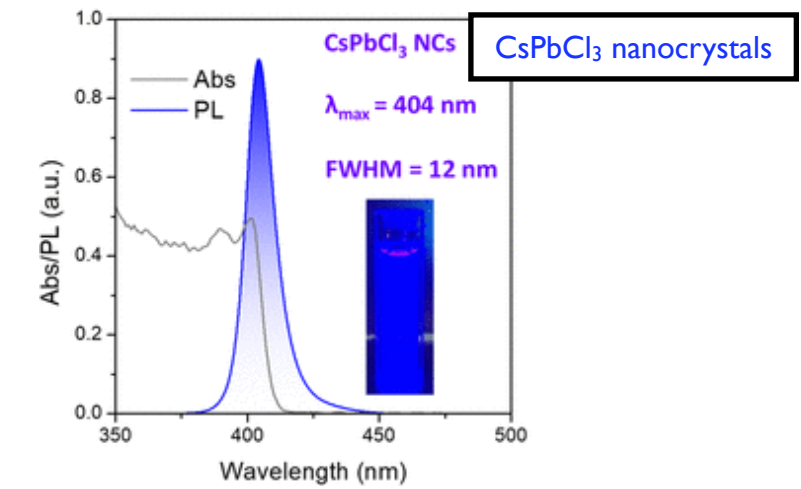
...

rightmost nanodots:
absorb wavelengths < 410 nm
emit at > 420 nm



triangular carbon nanodots

if high-Z substrate transparent
in 400-700 nm, then no re-
absorption of emitted light



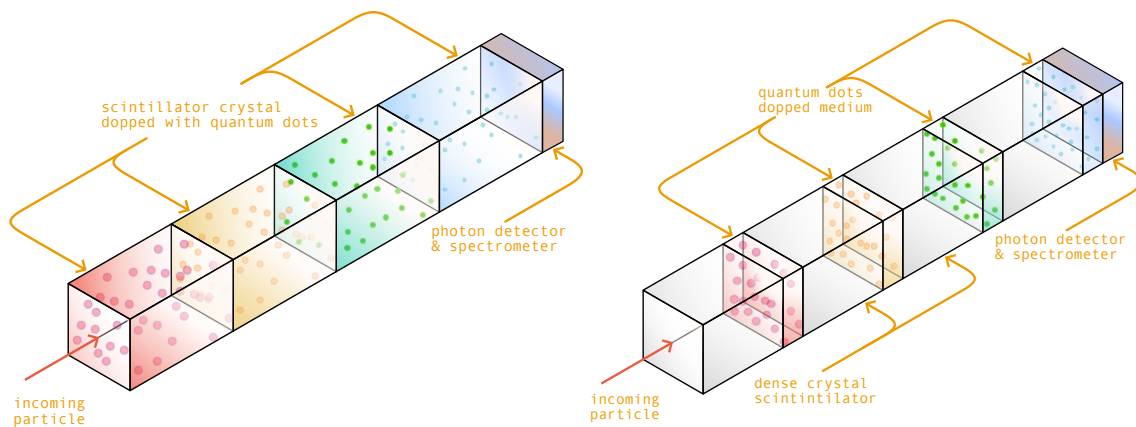
(shower profile via **spectrometry**)

Monochromators + PD?

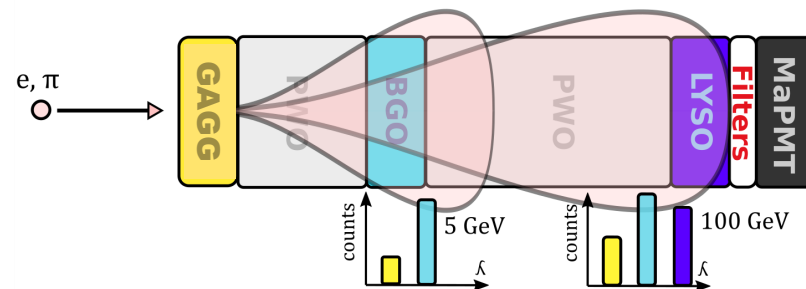
Y.T. Lin & G. Finlayson, Sensors 23, 4155 (2023)

Metalenses?

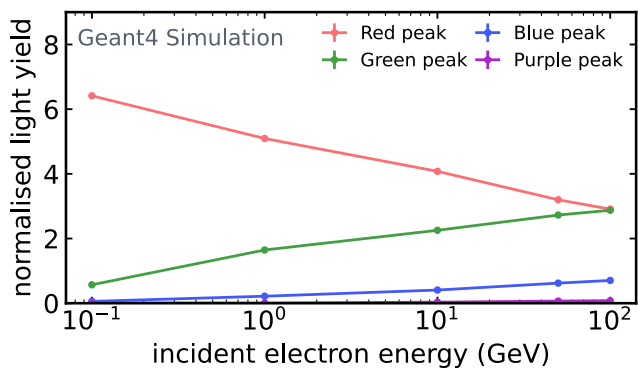
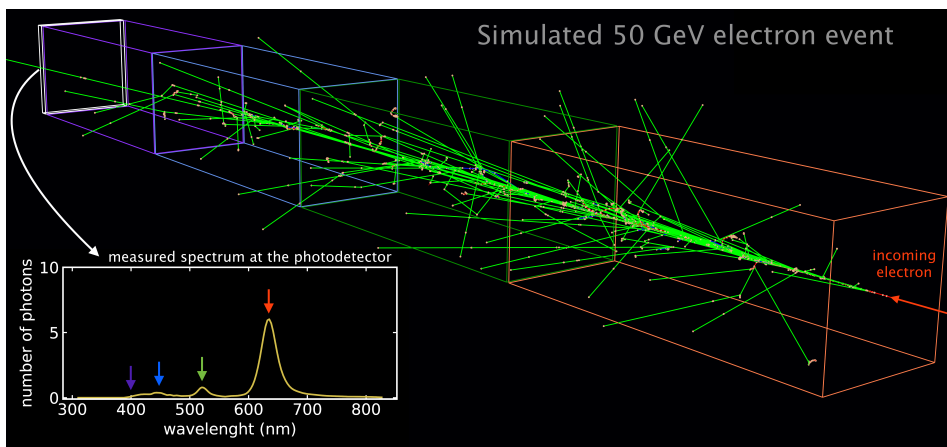
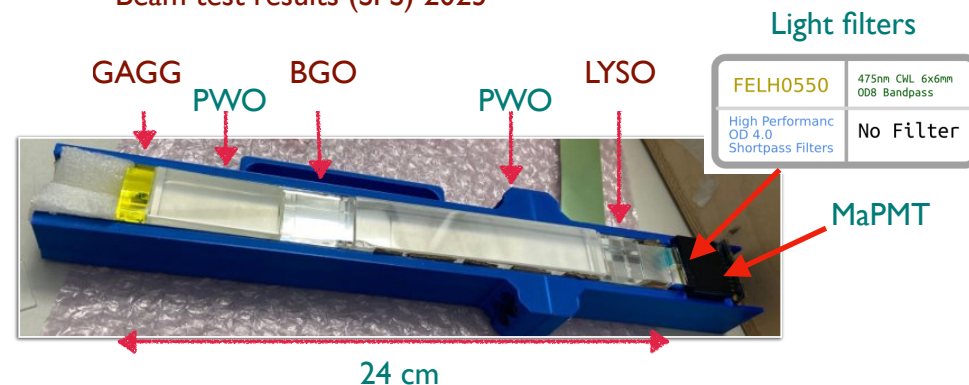
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)



courtesy Y. Haddad, N U, Boston, USA

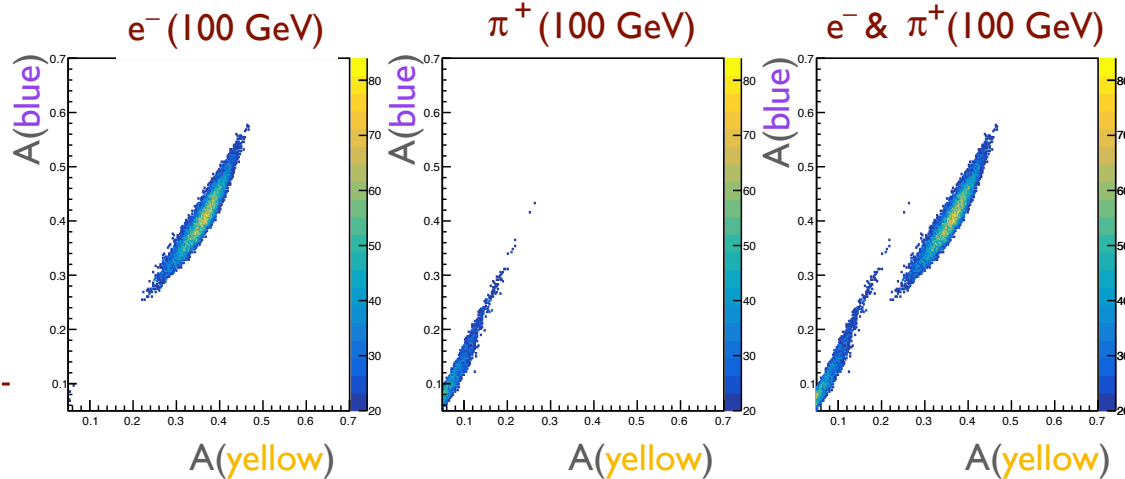


Beam test results (SPS) 2023



“Chromatic” energy measurement

“Chromatic” electron - pion discrimination

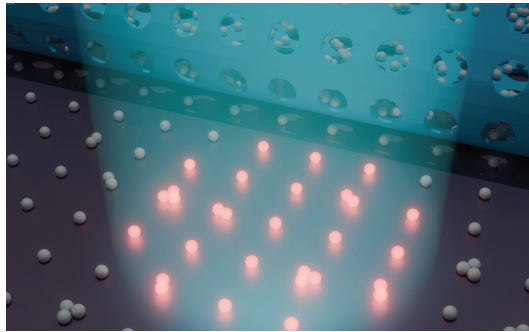


86% “chromatic” electron - pion discrimination

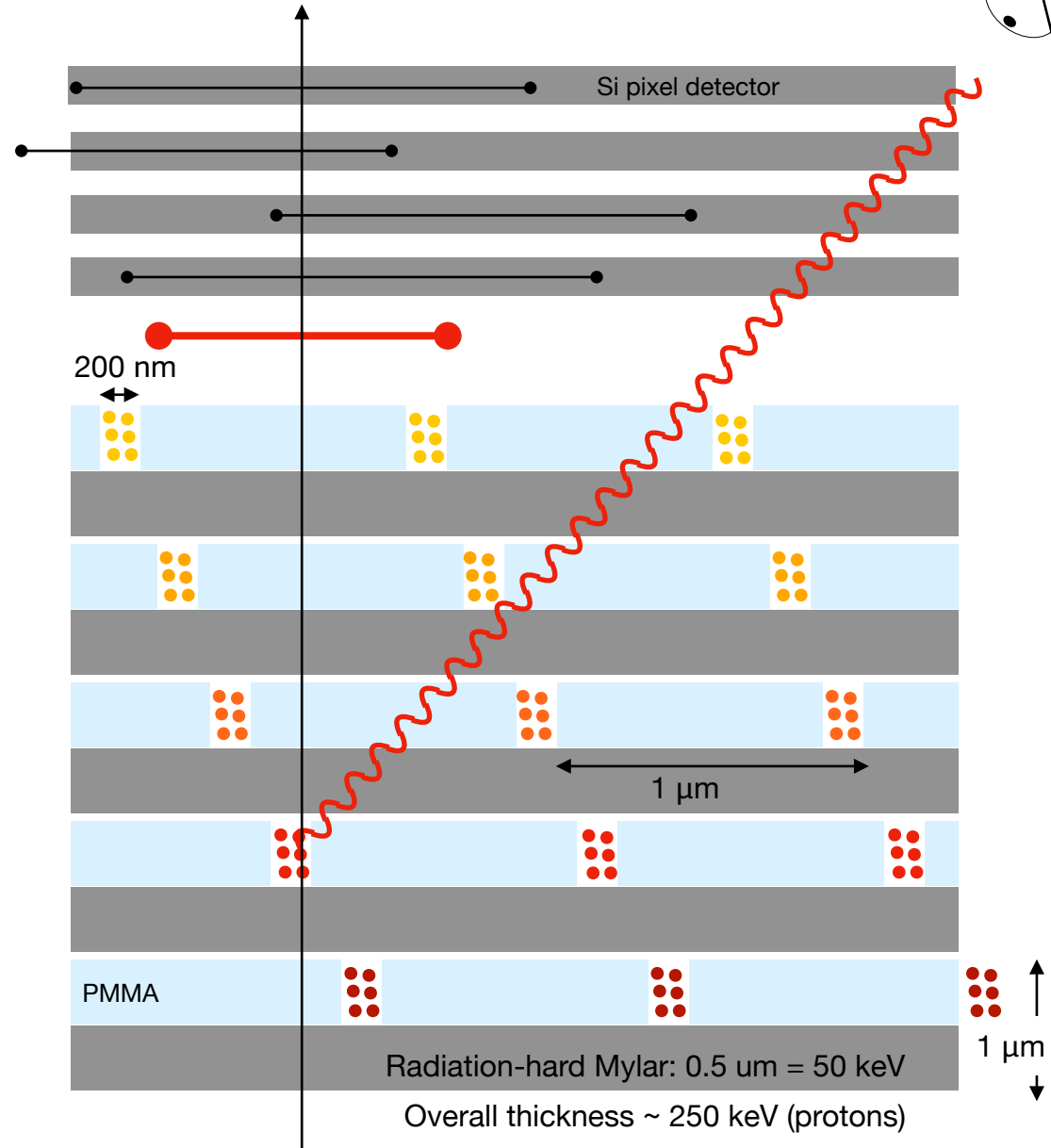
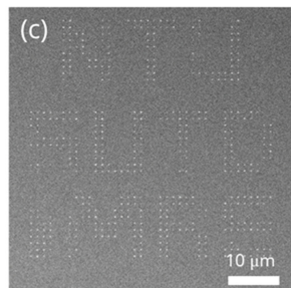
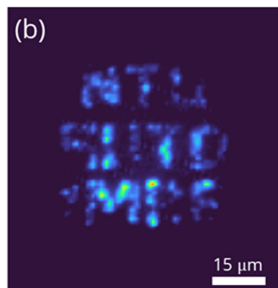
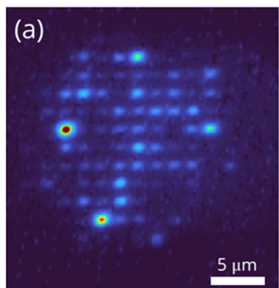
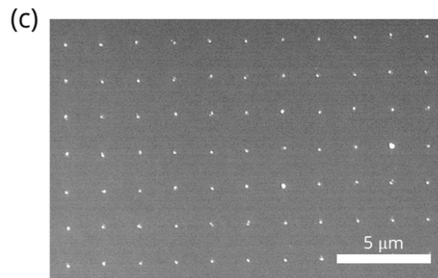
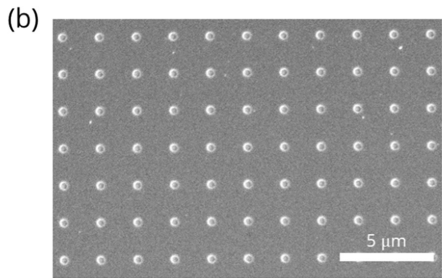
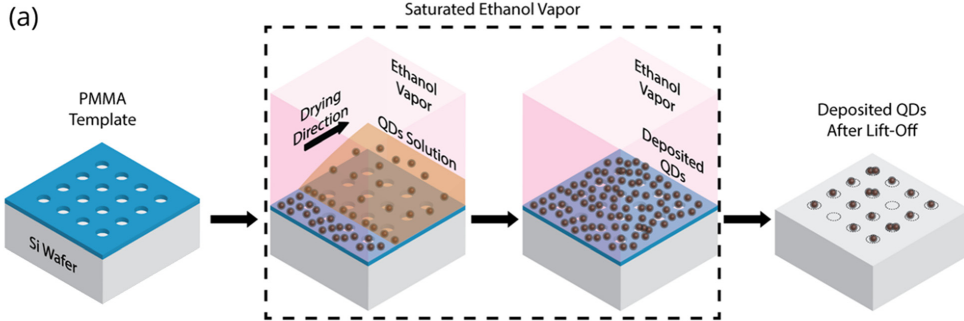
2 (IR) Quantum dots for HEP charged particle tracking

WP-2

Deterministic positioning of few aqueous colloidal quantum dots



Drying Process of Drop-Cast QDs Under Saturated Ethanol Vapor



Assembly positioning to < 100 nm

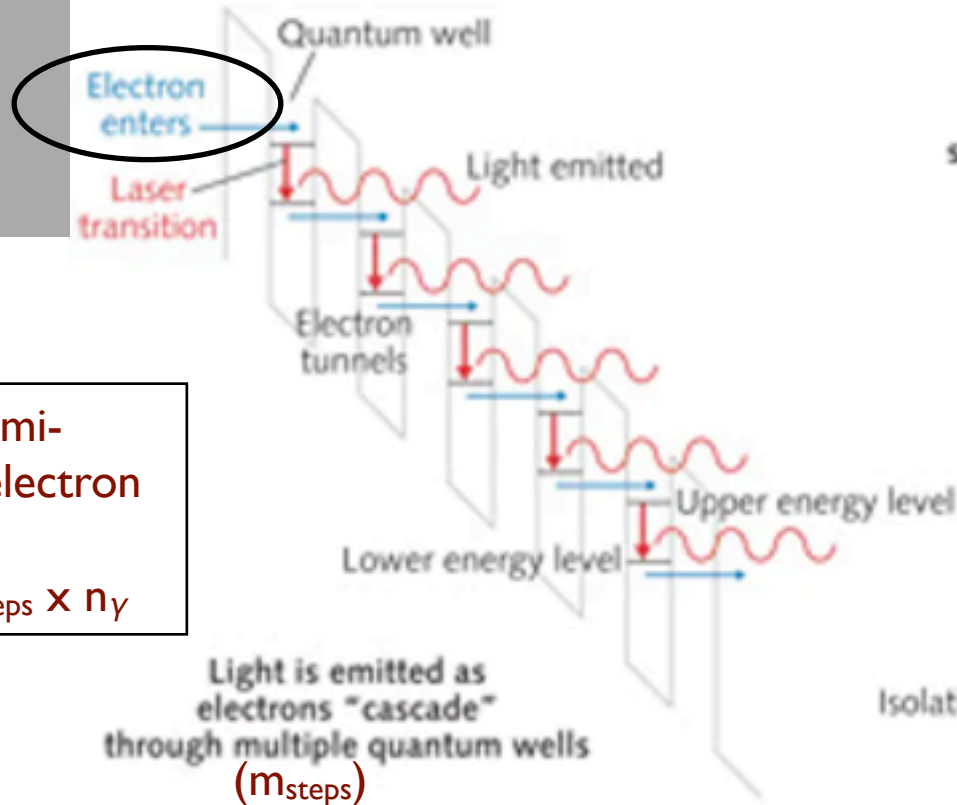
<https://xeryon.com/products/precision-linear-stages/xls-ultrasonic-linear-piezo-stage/>

Nanoscale, 2024, 16, 18339

https://ds.bilkent.edu.tr/wp-content/uploads/2024/10/Nanoscale1_2024_HVD.pdf

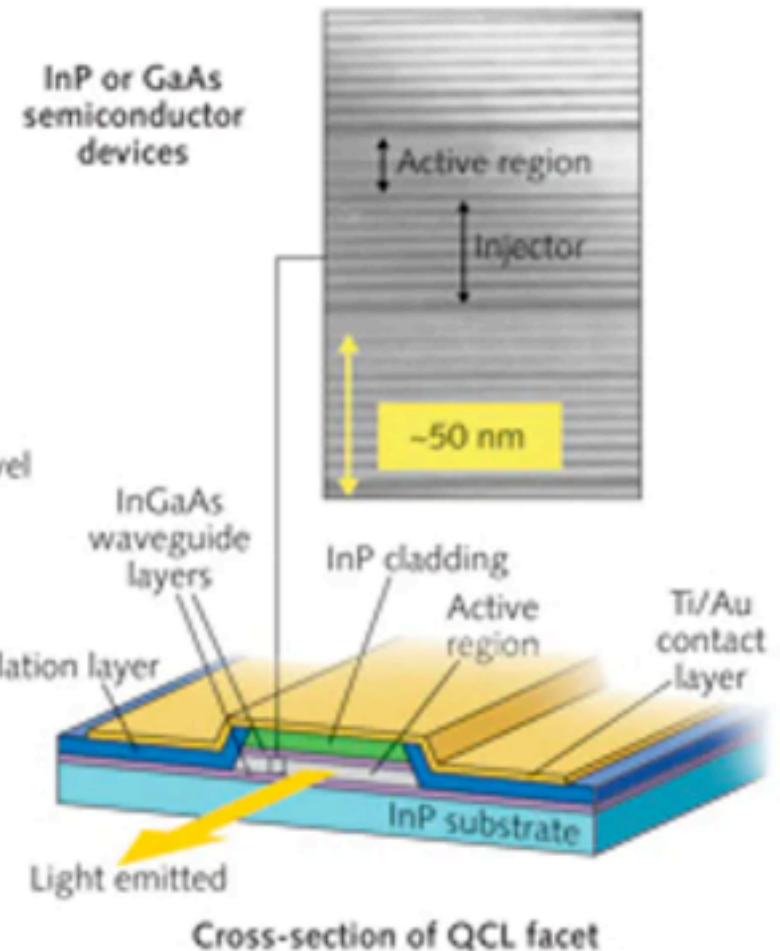
Active scintillators (QCLs, QWs, QDs, QWDs)

<https://www.laserfocusworld.com/test-measurement/spectroscopy/article/16556856/quantumcascade-lasers-qcls-enable-applications-in-ir-spectroscopy>



Couple bulk semiconductor to electron injection layer:

$$n_e \longrightarrow m_{\text{steps}} \times n_\gamma$$



Emitted light is IR~THz, normally mono-chromatic but tunable from 3 μm ~ 12 μm

Radiation resistant ([Radiation Physics and Chemistry 174](#), 2020, 108983)

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskites

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs)

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's

Spin-based sensors

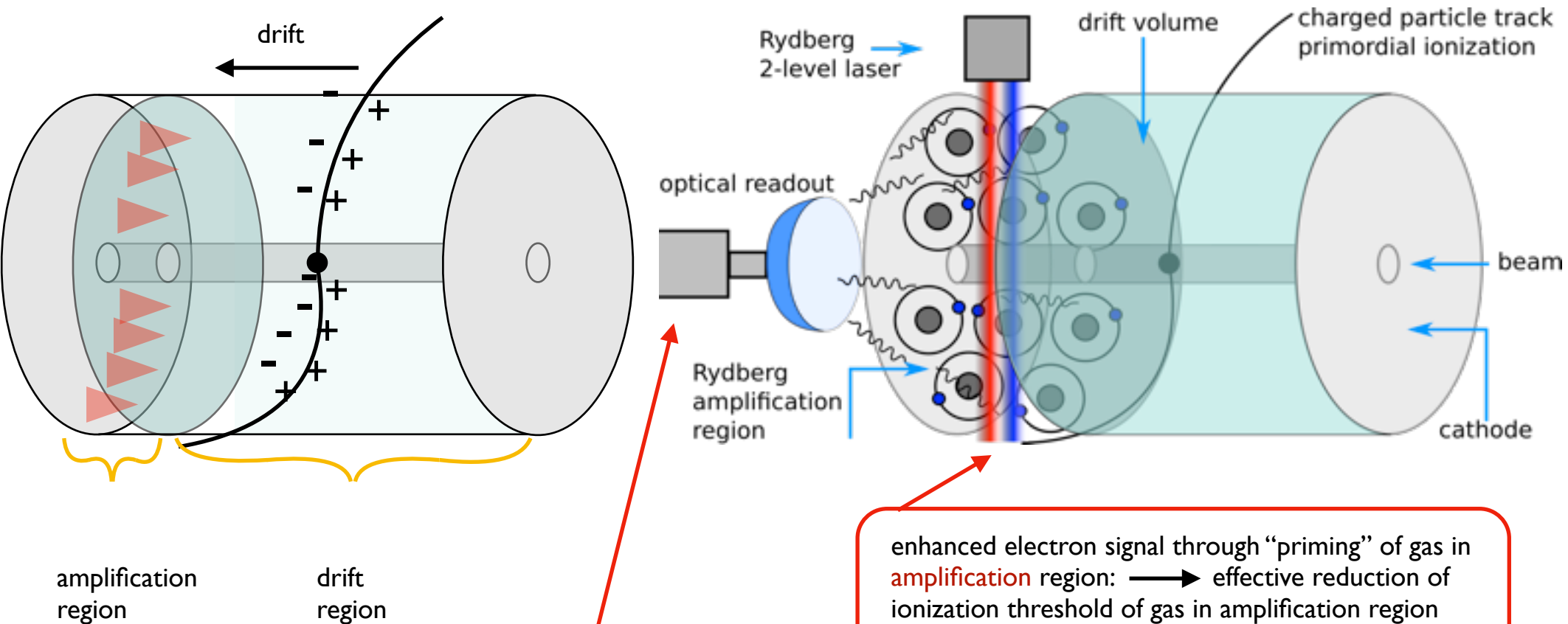
helicity detectors

Superconducting sensors

Rydberg atom TPC's

Georgy Kornakov / WUT

Act on the amplification region



enhanced electron signal through "priming" of gas in **amplification** region: \longrightarrow effective reduction of ionization threshold of gas in amplification region
 \longrightarrow higher electron yield

Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime \longrightarrow optical R/O of avalanche intensities

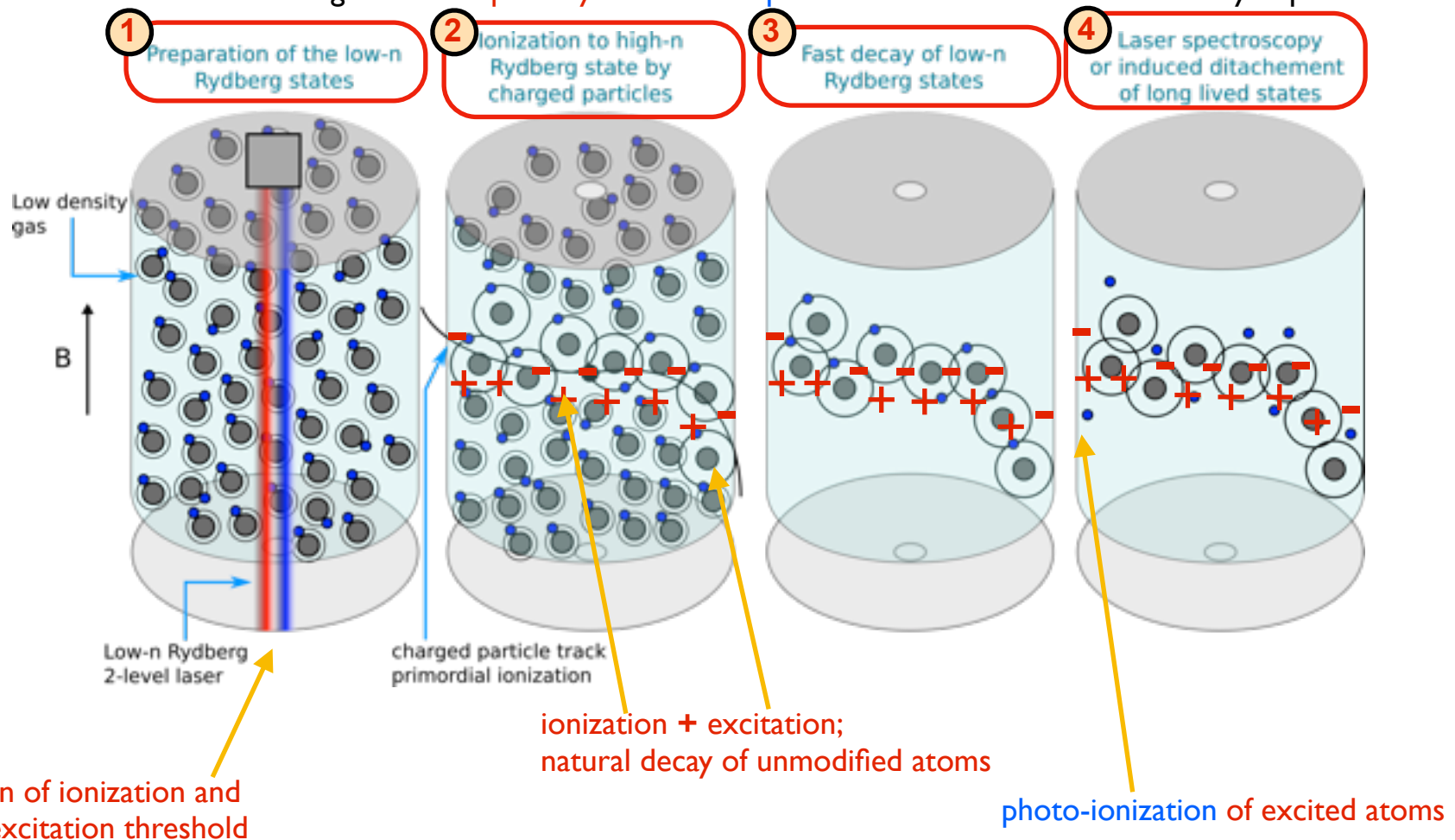
Act on the drift region

principle carries over to drift region:

enhanced electron signal through “priming” of gas in **drift** region:

effective reduction of ionization threshold of gas in amplification region

increased dE/dx through standard **primary** ionization + **photo-ionization** of atoms excited by mip's



Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

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chromatic calorimetry (QDs)

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Atoms, molecules, ions

Rydberg TPC's

Spin-based sensors

helicity detectors

Superconducting sensors

4

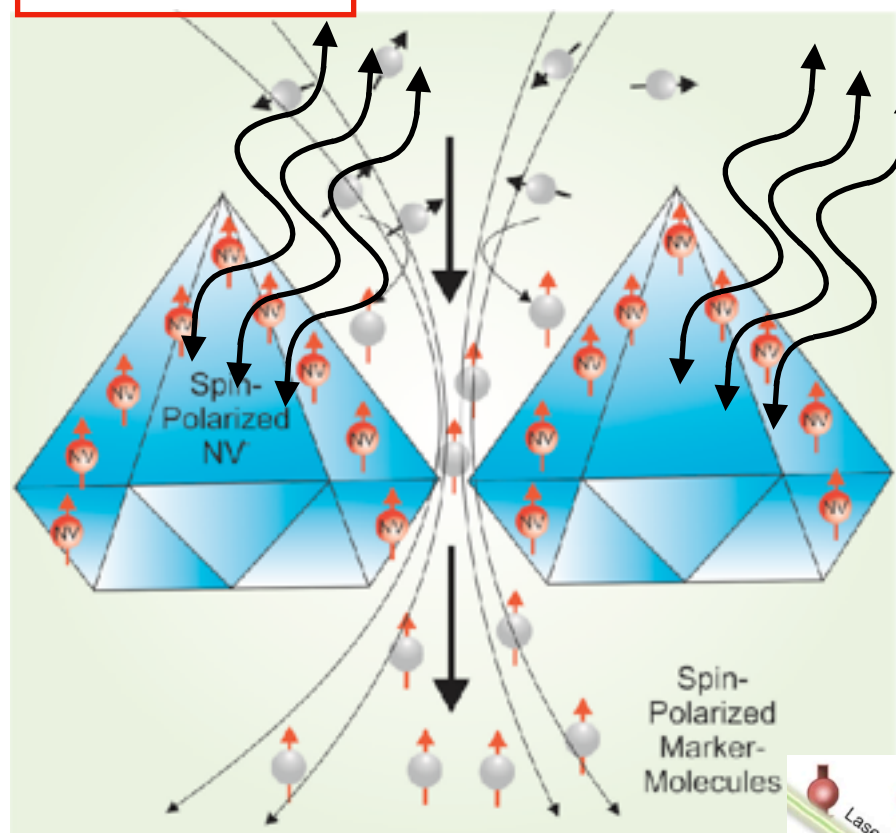
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

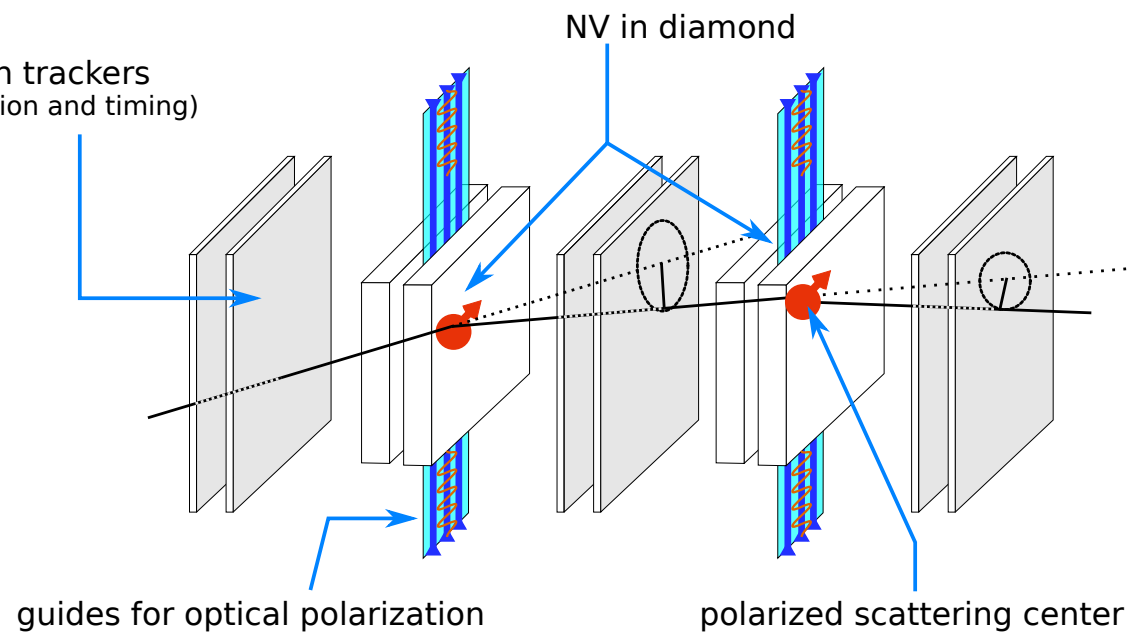
spin-spin scattering for helicity determination: usually with polarized beams and/or polarized targets

introduce polarized scattering planes to extract track-by-track particle helicity

$10^{16} \sim 10^{18} / \text{cm}^3$



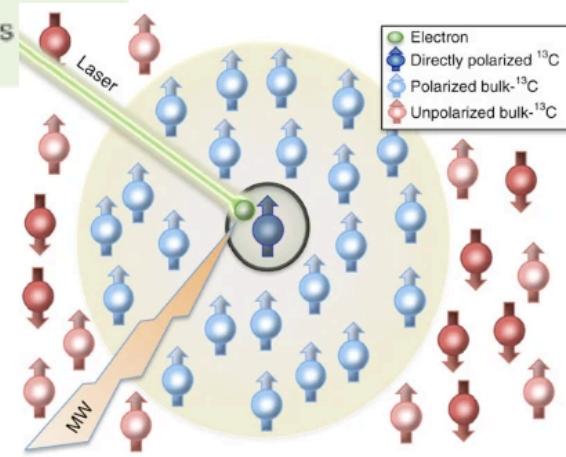
silicon trackers
(direction and timing)



© Dr. Christoph Nebel, Fraunhofer IAF

https://www.metaboliqs.eu/en/news-events/MetaboliQs_PM_first_year.html

Diamond plates of up to $8 \times 8 \text{ mm}^2$ in size, fabricated by Element Six



Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)
<https://www.nature.com/articles/ncomms9456>

$\times 10^2$

Xe (Kr,Ar) can be sympathetically **polarized** by interaction with optically polarized Rb

Spin Hyperpolarization in Modern Magnetic Resonance, J. Eills et al.,
Chem. Rev. 123 (2023), <https://doi.org/10.1021/acs.chemrev.2c00534>

Laser polarization of Rb

Liquification and transfer of Xe

K.L. Sauer et al., Chem. Phys. Lett. 277 (1997) 153

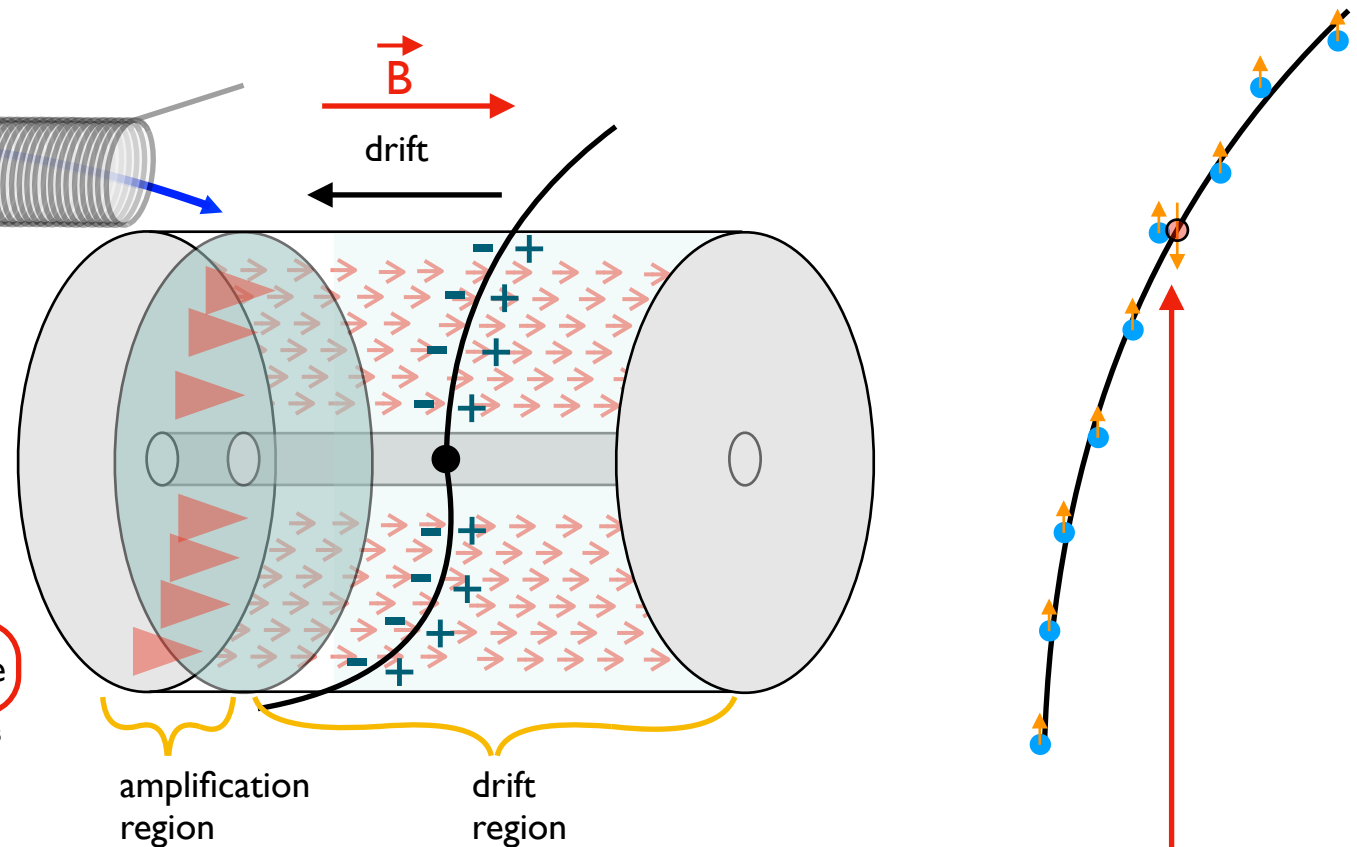
Transfer of Rb polarization to Xe

Spin exchange optical pumping hyperpolarization

G. Norquay et al., Phys. Rev. Lett. 121, 153201

Spin-spin scattering of helicity $+1/-1$ particle on polarized "target" \longrightarrow helicity determination

N. Lockyer et al., Phys. Rev. D 30 (1984) 860;
C.X. Lin et al., [arXiv:2512.02804v1](https://arxiv.org/abs/2512.02804v1) (2025);
Y.T. Liang et al., Phys. Rev. D 112 (2025) L031502



Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskites

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs)

GEMs (graphene)

Atoms, molecules, ions

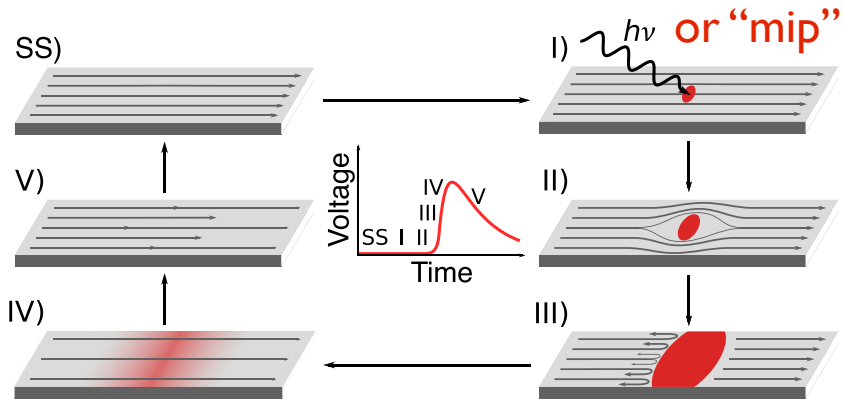
Rydberg TPC's

Spin-based sensors

helicity detectors

Superconducting sensors

4 Extremely low energy threshold detectors: SNSPD



SNSPD's Near term future

Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80% @ 10 μ m
Energy Threshold	0.125 eV (10 μ m)	12.5 meV (100 μ m)
Timing Jitter	2.7 ps	< 1ps
Active Area	1 mm ²	100 cm ²
Max Count Rate	1.2 Gcps	100 Gcps
Pixel Count	1 kilopixel	16 megapixel
Operating Temperature	4.3K	25 K

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

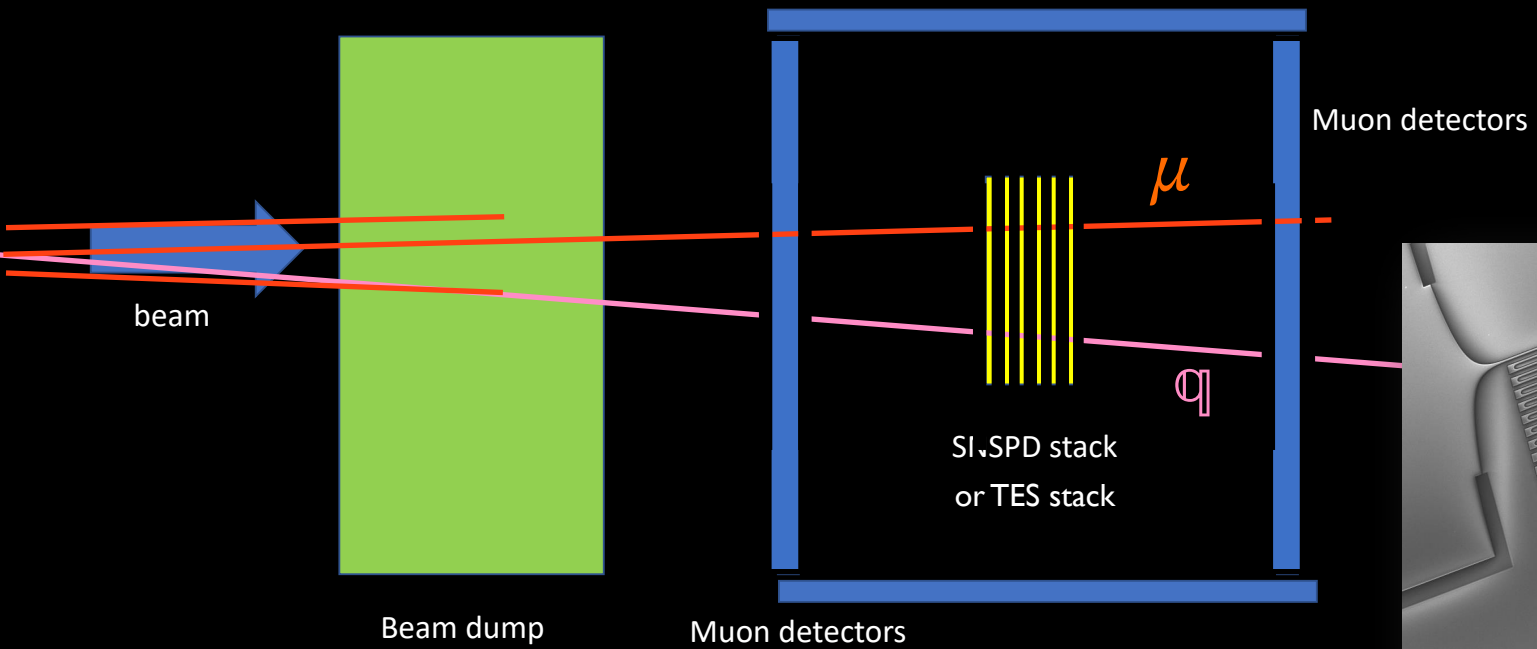
Moving to SC strips conventional lithography \rightarrow scale up
Development towards SC SSPM

Contact Information:
Karl Berggren, berggren@mit.edu
Ilya Charaev, charaev@mit.edu
Jeff Chiles, jeffrey.chiles@nist.gov
Sae Woo Nam, saewoo.nam@nist.gov
Valentine Novosad, novosad@anl.gov
Boris Korzh, bkorzh@jpl.nasa.gov
Matt Shaw, mattshaw@jpl.nasa.gov

QT4HEP22-- I. Shipsey

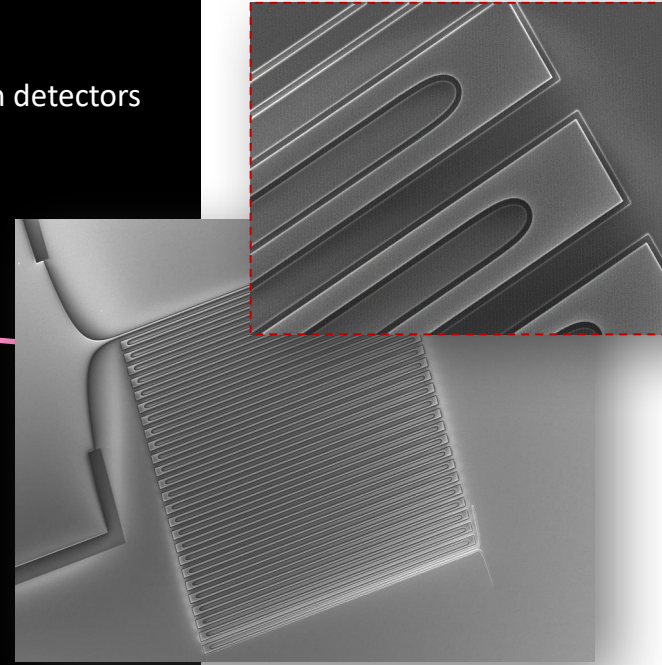
125

Search for Beyond Standard Model **milli-charged particles?**

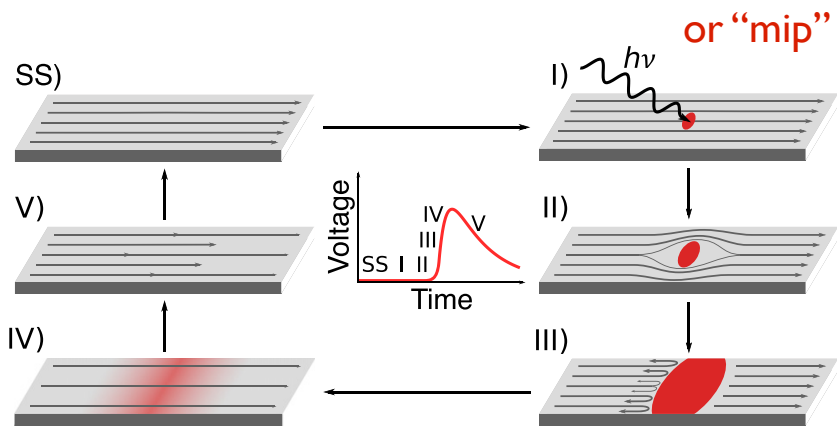


mip: ~ 20 keV/100 μ m

$\times 10^6$ sensitivity



4 Extremely fast detectors: SNSPD SNSPD's Near term future



Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @10 μ m
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Snowmass2021 - Letter of Interest

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Development towards SC SSPM

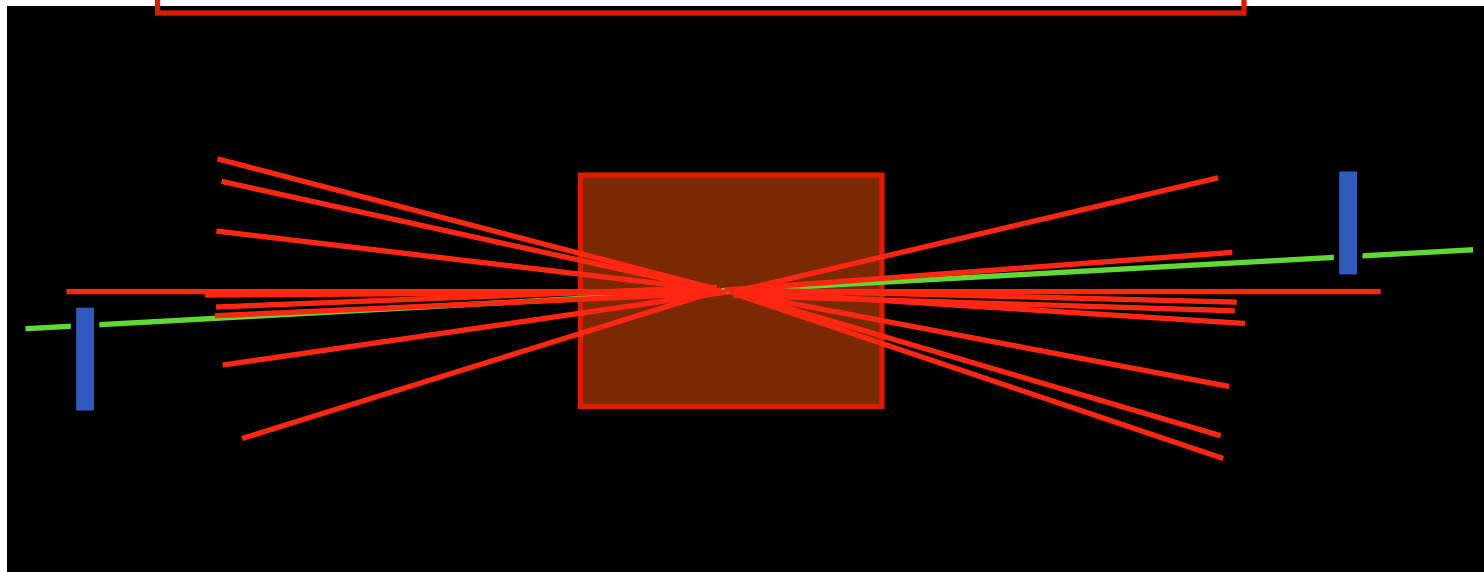
QT4HEP22-- I. Shipsey

Contact Information:

Karl Berggren, berggren@mit.edu
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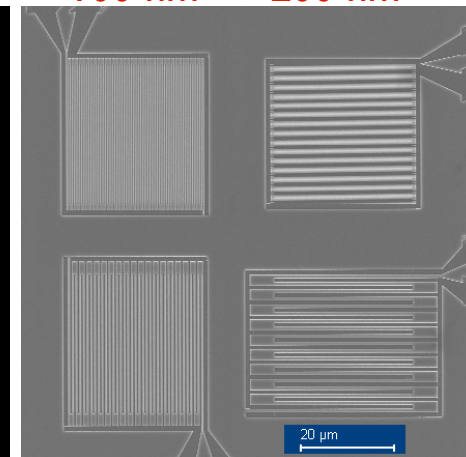
125

diffractive scattering via ps-resolution tracking in Roman pots



@ 2.8 K

100 nm 200 nm

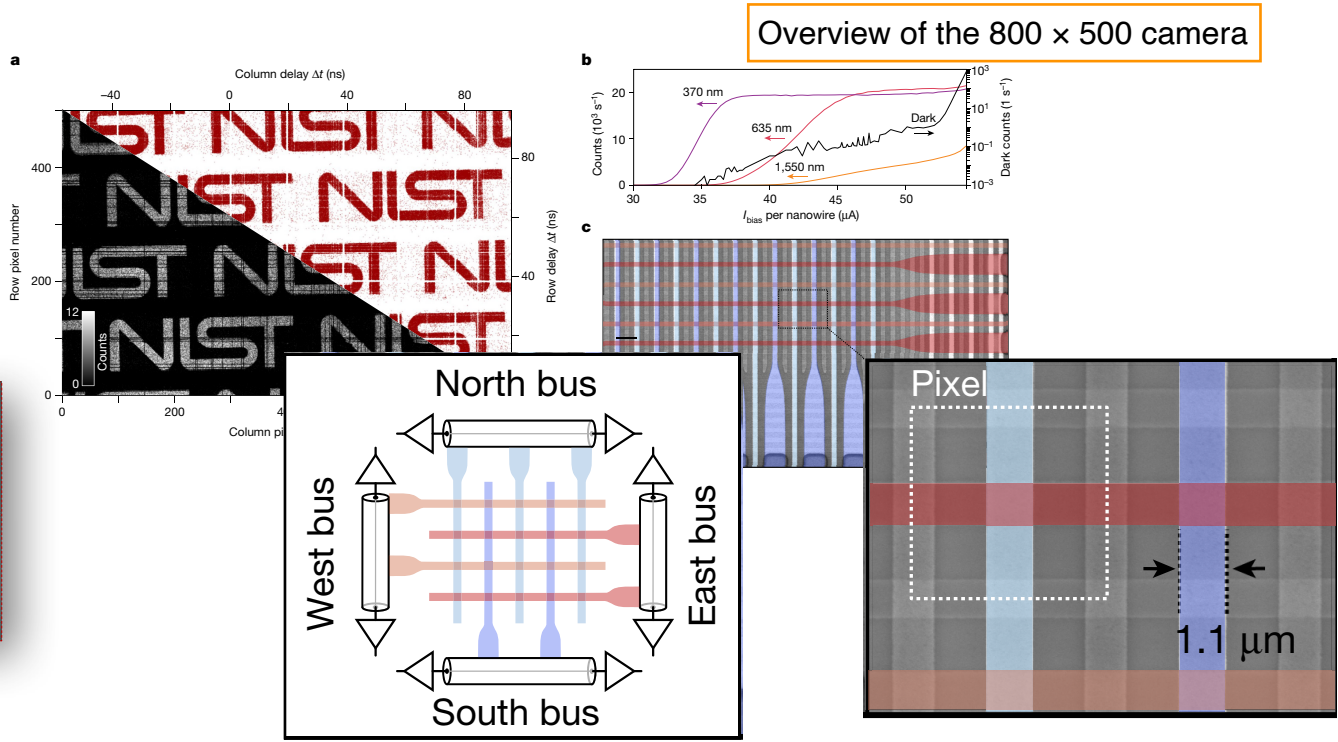
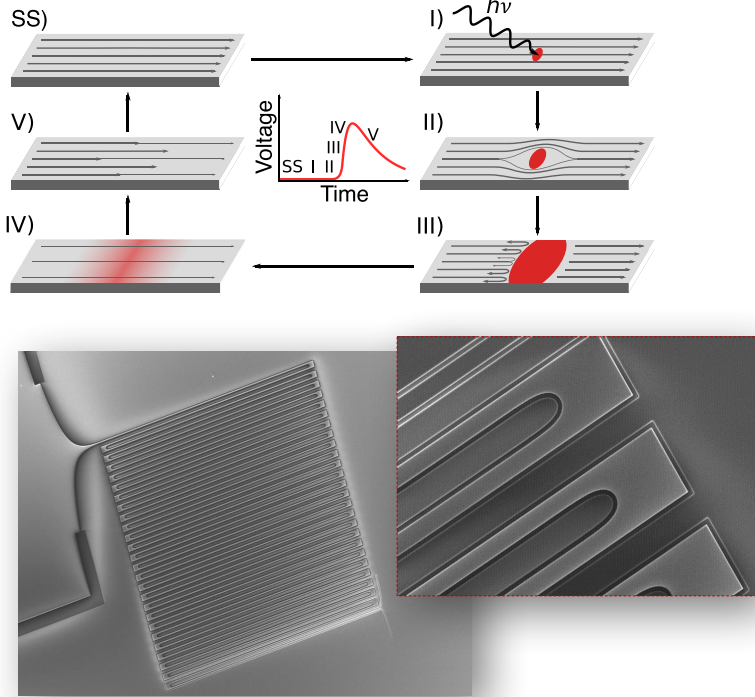


400 nm 800 nm

arXiv:2312.13405v2
[physics.ins-det]
5 Apr 2024

low energy particle physics: dark count rate is critical !
high energy particle physics: dark count rate is not a problem: high Tc is imaginable

4 Specific examples for potential particle physics impact: WP-3



SNSPD: Advances & Expected Performance

Operating Temperature	Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength
4.3 K	18 ps	None	93%	64	1 Gcps	4 /s/mm ²	0.001 cm ²	5 μm
25 K	2.6 ps [1]	3-5 photons	98% [2]	4x10 ⁵ [3]	1.5 Gcps [4,5]	4x10 ⁻⁵ /s/mm ² [6]	0.1 cm ² [3]	29 μm [7]
	1 ps	10	99%	10 ⁷	10 Gcps	1x10 ⁻⁶ /s/mm ²	1 cm ²	100 μm

Records in 2016

Current records for isolated devices

Expected performance by 2030

Multi-layer stacked det^s

- millicharged particles
- diffractive scattering
- luminosity monitor

[1] Korzh, Zhao et al, *Nature Photonics* 14, 250 (2020)

[2] Reddy et al, *Optica* 7, 1649 (2020)

[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, *Nature* 622, 730 (2023)

[4] Craiciu, Korzh et al, *Optica* 10, 183 (2023)

[5] Resta et al, *Nano Letters* (2023)

[6] Chiles, *PRL* 128, 231802 (2022)

[7] Taylor, Walter, Korzh et al, *Optica*, (2023)

“Quantum” is relevant
(focus on potential HEP impact)

HEP function		Tracking		Calorimetry		Timing		PID		Helicity		
Work package												
DRD5 WP	WP 1 (Quantum systems in traps and beam)		Rydberg TPC		BEC WIMP scattering (recoil)		O(fs) reference clock for time-sensitive synchronization (photon TOF)		Rydberg dE/dx amplifiers			
	WP2 (Quantum materials: 0-, 1- and 2-D)		“DotPix”; improved GEM’s; chromatic tracking (sub-pixel); active scintillators		Chromatic calorimetry		Suspended / embedded quantum dot scintillators		Photonic dE/dx through suspended quantum dots in TPC			
	WP 3 (Superconducting quantum devices)		O(ps) SNSPD trackers for diffractive scattering (Roman pot)		FIR, UV & x-ray calorimetry		O(ps) high Tc SNSPD		Milli- & microcharged particle trackers in beam dumps			
	WP 4 (scaled-up bulk systems for mip’s)		Multi-mode trackers (electrons, photons)		Multi-mode calorimeters (electrons, photons, phonons)		Wavefront detection (e.g. O(ps) embedded devices)				Helicity detector via ultra-thin NV optically polarized scattering / tracking stack	
	WP 5 (Quantum techniques)								Many-to-one entanglement detection of interaction			
	WP 6 (capacity building)		Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)									

(under way; in preparation; under discussion or imaginable applications; long-range potential)

HEP applications

- WP-2 Quantum dots (HEP calorimetry)
- WP-3 Superconducting devices (HEP, astroparticle)
 - Nano- and Microwires
 - TES, MMC (cryo-spectrometry)
- WP-1 Atomic & nuclear physics (exotic atoms, neutrino physics, clocks)
- WP-4 Spin-based sensors

Infrastructure @ CERN

CERN QTI

DRD5:WP's (particle physics > HEP)

WP1	<u>Exotic systems</u> in traps & beams (HCI's, molecules, Rydberg systems, clocks, interferometry, ...)	WP4	<u>Scaling up</u> to macroscopic ensembles (spins; nano-structured materials; hybrid devices, opto-mechanical sensors,...)
WP2	<u>Quantum materials</u> (0-, 1-, 2-D) (Engineering at the atomic scale)	WP5	<u>Quantum techniques for sensing</u> (back action evasion, squeezing, entanglement, Heisenberg limit)
WP3	<u>Quantum superconducting systems</u> (4K electronics; MMC's, TES, SNSPD, KID's/...; integration challenges)	WP6	<u>Capability expansion</u> (cross-disciplinary exchanges; infrastructures; education)

...in all the shown examples, dedicated R&D is under way, with involvement of DRD5

What is DRD5 built to do?

- focus on addressing topics that go *beyond what individual institutes* can do
- pool expertise, resources, create exchanges, educate
- create a global multi quantum-technology community focusing on quantum systems based detector R&D under the umbrella of DRD5

- Common R&D building on the extremely rapidly growing areas of quantum technologies
- Workshops
- Detector test facilities
- Education
- Agreements & standards
- ...

...in all the shown examples, dedicated R&D is under way, with involvement of DRD5

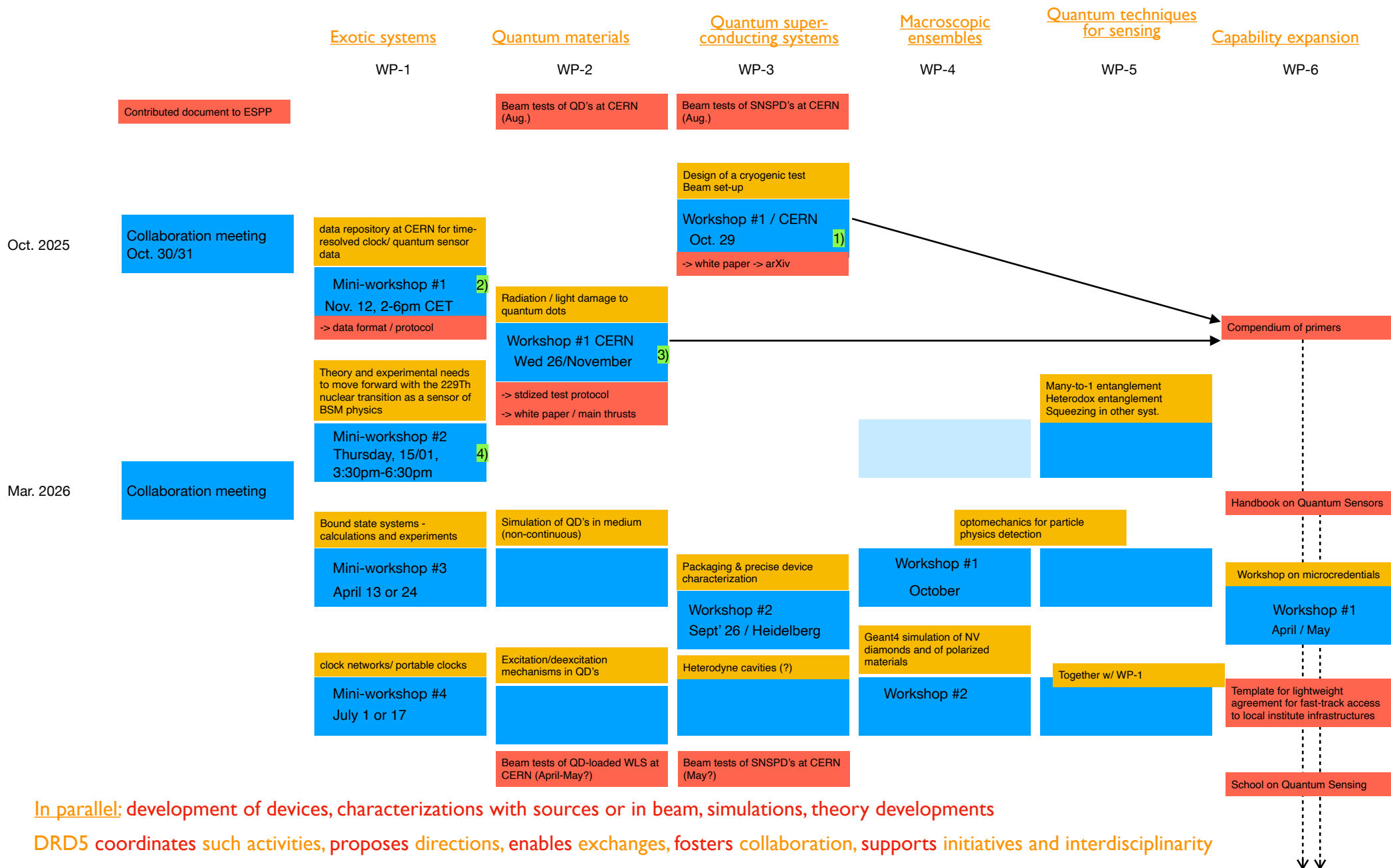
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- create a global multi quantum-technology community focusing on quantum systems based detector R&D under the umbrella of DRD5

What has happened since the DRD5 was formed and approved in mid-2024?

- concrete proposals for *HEP-relevant* uses of quantum sensors are appearing
- first beam tests with quantum dots and nano/microwires
- formation of a global multi quantum-technology community focusing on detector R&D under the umbrella of DRD5
- infrastructure needs have been identified and are starting to be addressed (cryogenic beam test facilities, quantum dot characterization infrastructure, ...)

DRD5 : ongoing and planned activities



In parallel: development of devices, characterizations with sources or in beam, simulations, theory developments

DRD5 coordinates such activities, proposes directions, enables exchanges, fosters collaboration, supports initiatives and interdisciplinarity

1) <https://indico.cern.ch/event/1580512/>

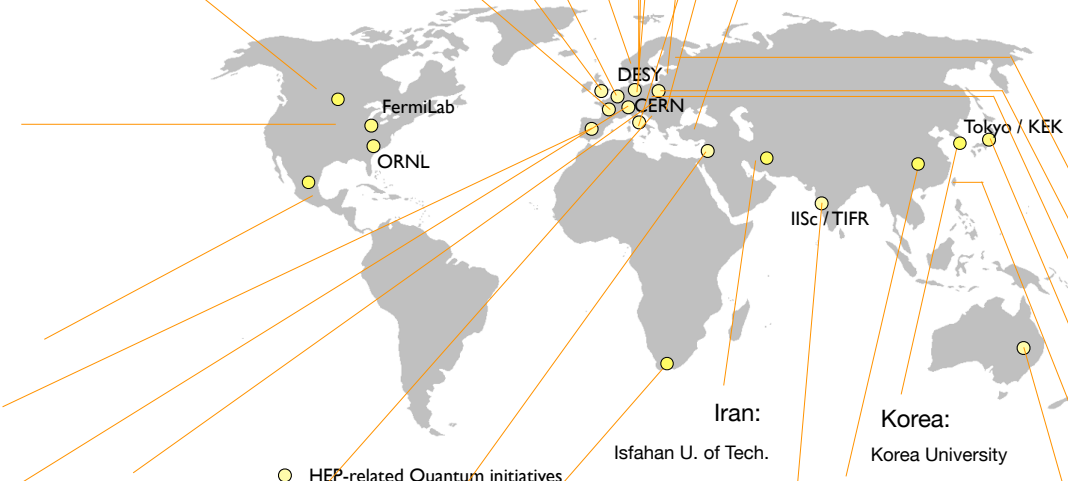
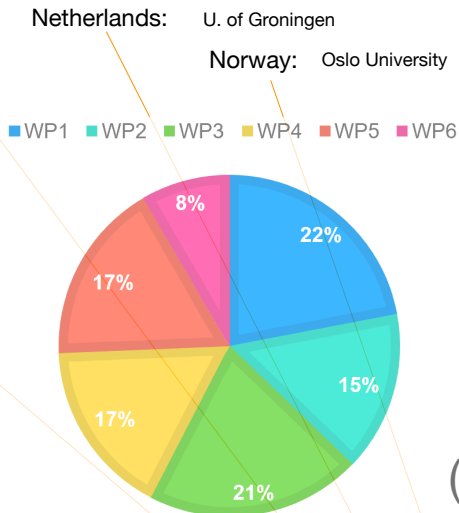
2) https://indico.cern.ch/event/1598214

3) https://indico.cern.ch/event/1598214

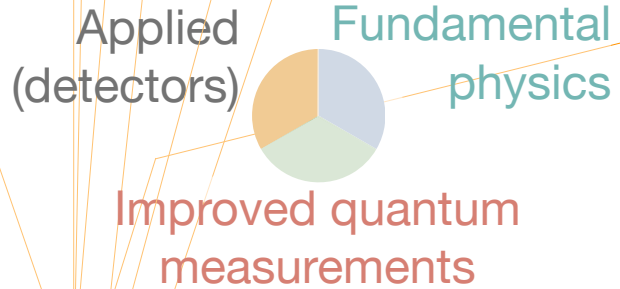
4) https://indico.cern.ch/event/1624634

DRD5: 120 involved groups

- UK:** Oxford University, Univ. of Warwick, Univ. of Birmingham, NPL, Imperial College, Univ. of Southampton, Univ. of Sussex, Univ. of Liverpool, Univ. of Manchester
- France:** SYRTE / OBSPM, CNRS - U. Sorbonne Paris Nord, LKB, ILM - University Lyon 1, IRFU / CEA Saclay
- Canada:** McGill Univ., TRIUMF
- USA:** UCLA, ORNL, Northwestern Univ., Caltech, MIT, Arizona State Univ., Yale, Univ. of Arizona, NIST, LBNL, Univ. of Delaware, FNAL, SLAC
- Mexico:** U. de Aguascalientes
- Spain:** U. de Zaragoza, U. de Cartagena, U. de Valencia, U. de Lleida
- Austria:** IQOQI Vienna, TU Wien
- Switzerland:** U. of Geneva, U. of Zürich, CERN, ETHZ, Univ. Bern
- Croatia:** Inst. of Physics, Zagreb



- Netherlands:** U. of Groningen
- Norway:** Oslo University
- Sweden:** Stockholm University
- Denmark:** Aarhus University
- Lithuania:** University of Vilnius
- Hungary:** Wigner Institute
- Türkiye:** Sabanci University, Istanbul; Düzce University; Ankara University, Ankara; Izmir University; Istinye University, Istanbul
- Italy:** U. of Pisa & INFN, U. of Pavia, U. of Firenze, U. of Milano-Bicocca, Fondazione Bruno Kessler, Trento; IOM CNR, Elettra Sincrotrone, Trieste; Univ. of Bari / INFN; INFN Padova; Univ. Roma 1 & 3; Univ. Napoli; INFN Roma Tor Vergata; INFN LNF; INFN Trento (TIFPA); INFN Torino; INFN LNL; INFN Lecce; INFN Roma Tor Vergata; U. of Camerino
- Finland:** Helsinki Inst. of Physics, VTT
- Poland:** Warsaw TU; Nat. Centre Nucl. Research / Warsaw; Nat. Lab. FAMO / Torun
- Czech Republic:** Charles Univ., Prague; Czech Tech. University; University West Bohemia
- Japan:** QUP / KEK; Kyoto University; Tokyo University / ICEPP; University of Shizuoka
- Taiwan:** Academia Sinica & NTU
- Australia:** University of Western Australia; Swinburne University of Technology; University of Sydney
- China:** IHEP; USTC (Hefei)
- Iran:** Isfahan U. of Tech.
- Korea:** Korea University
- India:** IITT, Tirupati; IEM, Kolkata; TIFR, Mumbai; LPU, Punjab; University SOA Bhubaneswar
- South Africa:** U. of Cape Town
- Israel:** Technion, Haifa
- Australia:** University of Western Australia; Swinburne University of Technology; University of Sydney



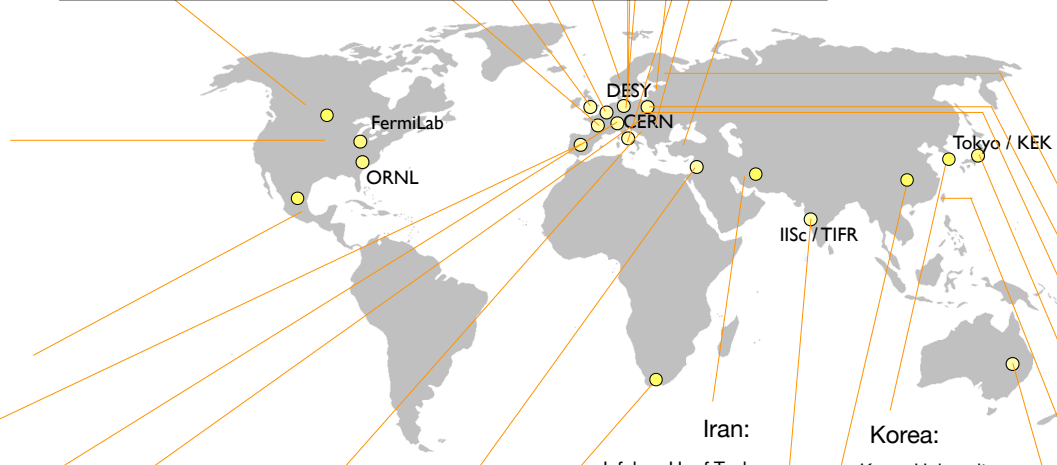
- Germany:** PTB, Univ. Ulm, Leibnitz Univ. Hannover, KIT, Karlsruhe, TU München, DESY, MPP Garching, HU Berlin, FBH Berlin, Univ. Heidelberg, Univ. Tübingen, Univ. Düsseldorf, Univ. Mainz, Univ. Bremen / ZARM, Semiconductor Lab HLL / MPG, TU Darmstadt
- Italy:** U. of Pisa & INFN, U. of Pavia, U. of Firenze, U. of Milano-Bicocca, Fondazione Bruno Kessler, Trento; IOM CNR, Elettra Sincrotrone, Trieste; Univ. of Bari / INFN; INFN Padova; Univ. Roma 1 & 3; Univ. Napoli; INFN Roma Tor Vergata; INFN LNF; INFN Trento (TIFPA); INFN Torino; INFN LNL; INFN Lecce; INFN Roma Tor Vergata; U. of Camerino
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- South Africa:** U. of Cape Town
- Israel:** Technion, Haifa

DRD5: 120 involved groups

Collaboration ramping up, combines diverse communities, including HEP.

Many novel developments that benefit both quantum technologies and particle physics.

Open to all interested parties (and it's free to join!)



- UK:** Oxford University
Univ. of Warwick
Univ. of Birmingham
NPL
Imperial College
Univ. of Southampton
Univ. of Sussex
Univ. of Liverpool
Univ. of Manchester

- France:** SYRTE / OBSPM
CNRS - U. Sorbonne Paris Nord
LKB
ILM - University Lyon 1
IRFU / CEA Saclay

- Canada:** McGill Univ.
TRIUMF

- USA:** UCLA
ORNL
Northwestern Univ.
Caltech
MIT
Arizona State Univ.
Yale
Univ. of Arizona
NIST
LBNL
Univ. of Delaware
FNAL
SLAC

- Mexico:** U. de Aguascalientes

- Spain:** U. de Zaragoza
U. de Cartagena
U. de Valencia

- Switzerland:** U. of Geneva
U. of Zürich
CERN
ETHZ
Univ. Bern

- Netherlands:** U. of Groningen

- Norway:** Oslo University

- Sweden:** Stockholm University

- Denmark:** Aarhus University

- Lithuania:** University of Vilnius

- Germany:**

- PTB
Univ. Ulm
Leibnitz Univ. Hannover
KIT, Karlsruhe
TU München
DESY
MPP Garching
HU Berlin
FBH Berlin
Univ. Heidelberg
Univ. Tübingen
Univ. Düsseldorf
Univ. Mainz
Univ. Bremen / ZARM
Semiconductor Lab HLL / MPG
TU Darmstadt

- Hungary:** Wigner Institute

- Türkiye:**

- Sabancı University, Istanbul
Düzce University
Ankara University, Ankara
Izmir University
Istinye University, Istanbul

- Italy:**

- U. of Pisa & INFN
U. of Pavia
U. of Firenze
U. of Milano-Bicocca
Fondazione Bruno Kessler, Trento
IOM CNR, Elettra Sincrotrone, Trieste
Univ. of Bari / INFN
INFN Padova
Univ. Roma 1 & 3
Univ. Napoli
INFN Roma Tor Vergata
INFN LNF
INFN Trento (TIFPA)
INFN Torino
INFN LNL
INFN Lecce
INFN Roma Tor Vergata
U. of Camerino

- Finland:**

- Helsinki Inst. of Physics
VTT

- Poland:**

- Warsaw TU
Nat. Centre Nucl. Research / Warsaw
Nat. Lab. FAMO / Torun

- Czech Republic:**

- Charles Univ., Prague
Czech Tech. University
University West Bohemia

- Japan:**

- QUP / KEK
Kyoto University
Tokyo University / ICEPP
University of Shizuoka

- Austria:** IQOQI Vienna
TU Wien

- Israel:** Technion, Haifa

- India:**

- IITT, Tirupati
IEM, Kolkata
TIFR, Mumbai
LPU, Punjab
University SOA Bhubaneswar

- South Africa:**

- U. of Cape Town

- China:** IHEP
USTC (Hefei)

- Korea:**

- Korea University

- Australia:**

- University of Western Australia
Swinburne University of Technology
University of Sydney

- Taiwan:**

- Academia Sinica & NTU

thank you!

WP-1a : Exotic systems in traps and beams

WP-1a_a: extension and improved manipulation of exotic systems

WP-1a_b: Bound state calculations

WP-1a c: Global analysis in the presence of new physics

WP-1b : Atom Interferometry

WP-1b a: Terrestrial Very-Long-Baseline Atom Interferometry Roadmap

WP-1b b: High-Precision Atom Interferometry

WP-1c: Networks, Signal and Clock distribution

WP-1c a: Large-scale clock network

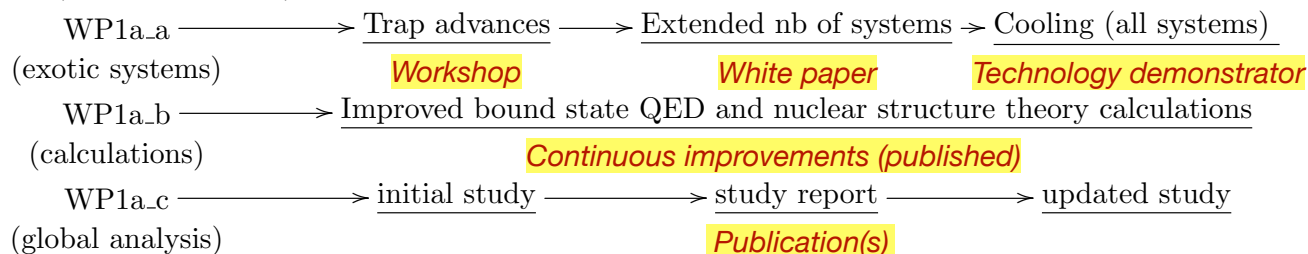
WP-1c b: Portable references and sources

cross-WP activity

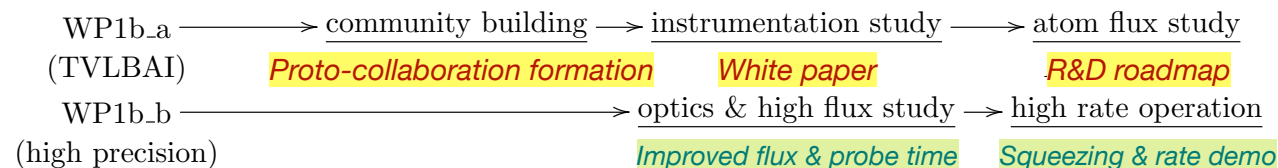
(Time and frequency distribution via space)

EXAMPLE

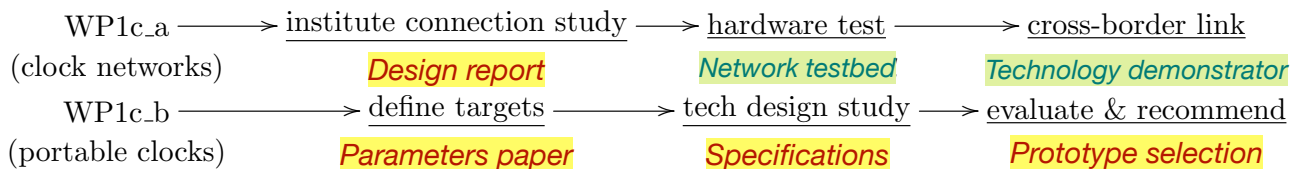
WP-1a (exotic systems)



WP-1b (interferometry)



WP-1c (clocks & networks)



WP-1a : Exotic systems in traps and beams

WP-1a_a: extension and improved manipulation of exotic systems

WP-1a_b: Bound state calculations

WP-1a_c: Global analysis in the presence of new physics

WP-1b : Atom Interferometry

WP-1b a: Terrestrial Very-Long-Baseline Atom Interferometry Roadmap

WP-1b b: High-Precision Atom Interferometry

WP-1c: Networks, Signal and Clock distribution

WP-1c a: Large-scale clock network

WP-1c b: Portable references and

cross-WP activity

(Time and frequency distribution via sp...

Our deliverables are (mostly) not definable in terms of technical specs, but rather in terms of community building

WP-1a (exotic systems)

WP1a.a → Trap advancement (exotic systems) → demonstrator
 WP1a.b → Bound state calculations (calculations) → demonstrations

atom flux study → atom flux study
 White paper → R&D roadmap
 optics & high flux study → high rate operation
 Improved flux & probe time → Squeezing & rate demo

WP-1c (clock networks)

WP1c.a → institute connection study → hardware test → cross-border link
 Design report → Network testbed → Technology demonstrator
 WP1c.b → define targets → tech design study → evaluate & recommend
 Parameters paper → Specifications → Prototype selection

Other ideas:

Super-radiance-based detectors

Quantum dots suspended in liquid TPC's